Volume 16 Number 12

# BULLETIN
*of the*
# AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS

DECEMBER 1932

## MAGNETIC RESURVEY OF OKLAHOMA CITY FIELD[1]

O. C. CLIFFORD, JR.[2]
Enid, Oklahoma

ABSTRACT

Comparative results of two magnetometer surveys, one in December, 1927, before the discovery of oil, and one in January, 1932, after production had reached maturity, show that the vertical component of the earth's magnetic field has been changed in detail by the presence of production equipment. The generalized magnetic pattern remains similar, however, for both surveys.

The first problem outlined at the initiation of an exploratory program of earth magnetics 5 or 6 years ago was, almost without exception, the definition of the vertical component pattern across well known and highly developed producing structures. The results of such surveys did not, in general, fit into the preconceived pattern as anticipated by the geologist-geophysicist. There were, however, such noteworthy exceptions as the buried extension of the Wichita Mountains in the Texas Panhandle and the southern portion of the Granite ridge in the vicinity of Eldorado, Kansas. With the knowledge that the magnetic pattern over these types of structure was so readily reconciled with the configuration of the granite, attempts were made at reconciling the known geological features in other areas with the measured magnetic anomaly, but these attempts proved, too frequently, unsuccessful. The geologist-geophysicist faced with the necessity for an explanation of phenomena with which he was little

[1] Read before the Association at the Oklahoma City meeting, March 25, 1932.

[2] Geologist-geophysicist.

acquainted, but concerning which he had definite convictions, expounded such hypotheses as the hysteresis induced by buried casing, the possibility of polar reversibility under the impact of cable tools, *et cetera ad infinitum*, being limited only by an inadequate vocabulary.

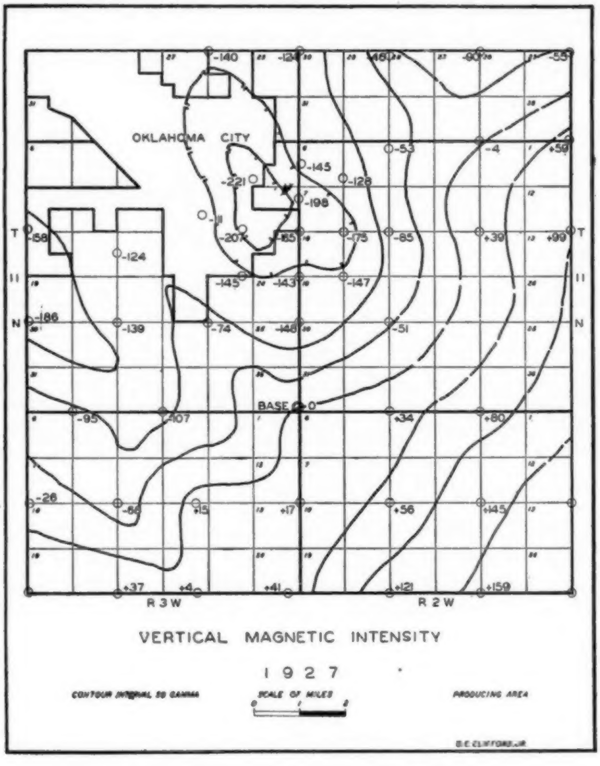



FIG. 1.—Map showing vertical magnetic intensity, 1927.

During the past 6 years the study of micro-geomagnetics has progressed beyond the limits of early credulity and, with the publications of Heiland, Wilson, Barret, Lynton, Spraragen and others, many of these problems are nearing solution. Though other geophysical methods have rightfully supplanted magnetic methods throughout most of the Mid-Continent and Gulf Coast areas, mag-

netometers must still be considered of exploratory value for specialized structural types and for rapid, inexpensive surveys of regional character.

There has been no material published, with one exception, on the measured change in the vertical component of the magnetic field in an area surveyed both before the discovery of production and after development had reached maturity. Barret[1] has published an interesting summary of such work in the Sligo field, Bossier Parish, Louisiana, which must be considered inconclusive because of the small number of control points. With the permission of the management of the Indian Territory Illuminating Oil Company, the results of two magnetic surveys in the vicinity of Oklahoma City are presented.

In December, 1927, a magnetic survey of the vertical intensity anomaly was completed in the vicinity of Oklahoma City, with the use of a Schmidt vertical intensity variometer manufactured by the American Askania Corporation. The results of this survey contoured on a 50-gamma interval are shown in Figure 1. The dominant feature is an area of negative relief centered around the west half of Sec. 12, T. 11 N., R. 3 W. Here a 110-gamma closure is the maximum observed. No attempt is made to interpret this feature with respect to the existence of Permian, Pennsylvanian, Ordovician, or pre-Cambrian structure. The structure was undoubtedly there and the magnetic picture appeared as shown.

The discovery well of the present Oklahoma City field was spudded in near the center of the SE. ¼ of the SE. ¼ of Sec. 24, T. 11 N., R. 3 W., June 12, 1928, and was completed December 4, 1928. An intensive drilling campaign followed and by January 1, 1932, a total of 867 wells had been completed, of which 5 had been abandoned. This represents, according to Charles,[2] a development of 80 per cent of all acreage which is thought to have possibilities of becoming productive. The structural conditions of Oklahoma City have been described by Charles[3] and others.

In mid-January, 1932, a resurvey of the vertical component of the earth's magnetic field was made. The results are shown in Figure 2, also contoured on a 50-gamma interval.

[1] William M. Barret, "Magnetic Disturbance Caused by Buried Casing," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 11 (November, 1931), pp. 1387–88.

[2] H. H. Charles, verbal communication.

[3] H. H. Charles, "Oklahoma City Oil Field," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 12 (December, 1930), pp. 1515–33.

There appears, at first glance, to be a marked discrepancy between the work of 1927 and that of 1932. This becomes less noticeable on closer scrutiny. The dominant feature of the later survey, also, is an area of negative relief, but this has been shifted from the west half

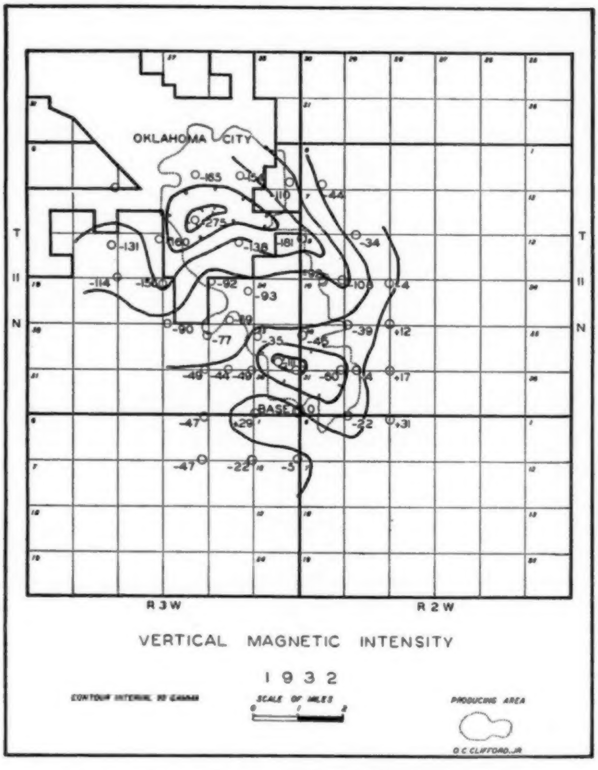



FIG. 2.—Map showing vertical magnetic intensity, 1932.

of Sec. 12, T. 11 N., R. 3 W., to the SE. ¼ of Sec. 10, T. 11 N., R. 3 W. The maximum closure appears to be approximately the same, though it may be greater in the later work. In the recent survey, the contours lie closer together and the general pattern practically duplicates that of 1927, but the plane of the feature appears to have been tilted toward the west.

The base point, SE. corner, Sec. 36, T. 11 N., R. 3 W., is identical for both surveys and is thought to be in an undisturbed state, as no well is closer to it than 3/8 mile. Between the base and a point two miles farther east, also in an undisturbed condition, there is a marked accordance of anomaly, a difference of plus 34 gammas being measured in the first survey and a difference of plus 31 gammas in the second survey. The stations south and west of the base point, though they do not coincide, either in position or value, do roughly correspond. It appears, then, that in the undisturbed area on the south there is a pronounced accordance of anomaly value which gives a reasonable check on the comparative accuracy of the two surveys.

The most pronounced discordance between the two surveys appears one mile north of the base station. In the original survey this point falls on a gradual northward decline of anomaly which continues uninterrupted for 5 miles. In the more recent work, there is a sharp decline of intensity in the first mile, followed by an almost equally sharp rise in the succeeding mile. Though every effort was made to keep pronounced effects of extraneous material from the survey, it is thought that this discrepancy represents such effects. When the instrument gave readings off the field of view, it was moved until large effects appeared vitiated.

The changed aspect of the vertical component map may be attributed to one or all of several factors. No attempt is made to evaluate the relative importance of these. They are: (1) the recent survey was more compactly observed and for that reason the intensity changes may appear more accentuated than in the original survey; (2) the physical development produces major changes in the magnetic field; (3) the actual extension of Oklahoma City proper, both laterally and vertically, has produced immeasurable changes in the magnetic field; and (4) secular variation causes slight differences.

The results from one resurvey of this type can not be considered conclusive. It is reasonable to expect, however, that similar attempts in other areas will produce similar results. The results of the present survey tend to show that, with care in the selection of observation points, the general picture of an area will show little difference before and after the development of production; that, if the original magnetic structure had any considerable relief, it will retain not only the same approximate closure, but also closure in the same direction. The early magnetic work in existing fields can thus be expected to have shown a rough approximation to the pre-development state.

It is hoped that similar surveys will be undertaken in areas which were magnetically defined prior to the discovery and development of production. A resurvey of Hobbs field, New Mexico, and various of the Permian basin fields of Texas should show interesting relationships.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1177-1203, 10 FIGS.

# MAGNETIC VECTOR STUDY OF REGIONAL AND LOCAL GEOLOGIC STRUCTURE IN PRINCIPAL OIL STATES[1]

W. P. JENNY[2]
Dallas, Texas

## ABSTRACT

The local magnetic vectors at the United States Coast and Geodetic Survey stations in Louisiana, Texas, Arkansas, Oklahoma, Kansas, Mississippi, Alabama, and California have been computed by deducting the normal values of the earth's magnetic field from the absolute measurements, at each station, of the declination and of the vertical and horizontal magnetic intensities.

The local magnetic vectors have been plotted as vector triangles at the respective stations on the vector maps of the different states.

These vectors indicate the intensity and the direction in space of the magnetic lines of force, as due to local magnetic anomalies mainly within the first 15,000 feet of subsurface.

As local magnetic anomalies are, with negligible exceptions, the result of geologic features, either of structural or petrographic character, a large amount of regional and local geologic information is obtained by a study of these maps.

The main magnetic anomalies of the different states have been interpreted in terms of geology, though no attempt has been made to exhaustively interpret all vectors.

The vector maps show at a glance which areas are of interest for magnetometer surveys, what size anomalies may be expected, how far a magnetometer survey has to be extended, or where it is best commenced to cover a certain area.

As the vectors are of sufficient accuracy, they allow a checking and tying-in of scattered magnetometer surveys.

## INTRODUCTION

Extensive studies of the anomalies of the magnetic vertical intensity and their correlation with geology were made some years ago in Europe,[3] in the Mid-Continent and Gulf Coast areas[4] and in California.[5]

[1] Read in part before the Association at the Oklahoma City meeting, March 25, 1932. Manuscript received, May 18, 1932.

[2] Geologist and geophysicist, 6241 Richmond Avenue.

[3] A. Nippoldt, "Karten der Verteilung des Erdmagnetismus und seiner oertlichen vertikalen Stoerungen in Europa," *Archiv des Erdmagnetismus*, Heft 6 (Julius Springer, Berlin, 1927).

[4] Magnetometer survey of seven states in the Mid-Continent and Gulf Coast regions, by L. Spraragen, series of articles published in the *Oil and Gas Journal* (1928–29).

[5] G. B. Somers, "Anomalies of Vertical Intensity Compared with Regional Geology for the State of California," *Colorado School of Mines Magazine* (September, 1929).

The investigations were based on the measurements made by the surveys of the respective European states, and by the United States Coast and Geodetic Survey.[1]

Though by these studies a definite connection between broad structural features—such as the West Texas Permian basins, the Central Mineral region, the main geological trends in California and Europe—and magnetic anomalies of the vertical intensity could be definitely established, such studies could only incidentally yield any information about the type of structure which is of special interest

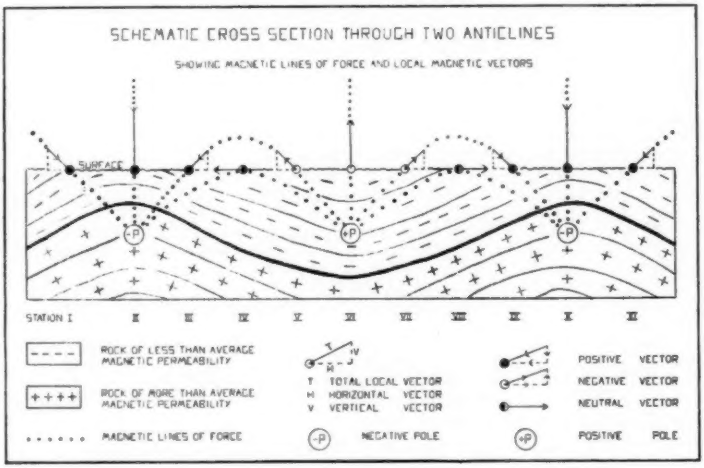



FIG. 1

to the commercial geologist, because the distances between the magnetic stations, ranging from 20 to 50 miles, were far too large.

It is quite evident that two, three, and more magnetic "highs" and "lows" may occur between stations placed at such distances and the lines of equal magnetic intensity, drawn on the base of such stations, as a rule veil, rather than set forth, the local magnetic anomalies which are due to small "structures."

Study of Figure 1 will make the previous statement clear. This cross section through two anticlines separated by a syncline demonstrates schematically the paths of the magnetic lines of force and the

[1] "United States Magnetic Tables and Magnetic Charts for 1925 by U. S. Department of Commerce," *U. S. Coast and Geodetic Survey Serial 453.*

local magnetic vectors as due to the local "structures" only, after the normal magnetic field of the earth has been eliminated. The total local vector is shown to be resolvable into two components—the local vertical and the local horizontal magnetic vector.

We have assumed that the material of the anticlines is of more than average magnetic permeability and the material of the syncline of less. Thus the magnetic "high" corresponds with a structural "high," and the magnetic "low" with a structural "low." This is the ordinary condition, for example, if two granite ridges are embedded in shales and limestones. Should the material of the anticlines be of less than average magnetic permeability and the material of the syncline of more, then the shape of the magnetic lines of force remains the same, but their direction is opposite to the direction shown in the picture. Thus a magnetic "low" would correspond with a structural "high" and vice versa. This condition exists in many places, for example in Kansas, where granite plugs or ridges pierce through the overlying highly magnetic schists.

For a clearer understanding, let it be assumed that the magnetic effects of the two anticlines and the syncline are equivalent to the effects of two negative ($-$P) poles, and one positive ($+$P) pole, as shown in Figure 1.

Above the negative poles the magnetic intensity is directed perpendicularly downward toward the poles (positive vector). Above the positive pole the magnetic intensity is directed perpendicularly upward, away from the pole (negative vector). Along the surface, half way between the positive and negative poles, the two vertical tendencies compensate each other and only a horizontal component remains, directed from the positive toward the negative pole (neutral vector). Between the vertical and horizontal directions of the intensity there occurs a gradual change, as shown in the picture. As long as the vector is still directed downward, it may be called a positive vector; if the direction is upward, a negative vector.

It might happen now that stations I and III had been occupied by the Coast and Geodetic Survey. As both stations have the same magnetic vertical intensity they lie on the same isogam, which would pass over the entire structure without taking the slightest notice of it. The same would happen, if also stations III and IX had been surveyed. Any other combination of the vertical intensity of two or three stations give widely varying indications of some anomaly. We should consider, however, that most of the "structures," which create

the local anomalies, lie at depths ranging from 2,000 to 15,000 feet and that the magnetic effect is felt within a horizontal distance from the edge of a "structure" of only about twice its depth. Therefore it is reasonable to assume that, within a distance of 20–50 miles, only one station is occupied, as a rule, on a particular "structure" and there is little use in combining the measurements of the different stations, unless broad structural features are suspected.

Contrary to the opinion of some magneticians,[1,2] the writer holds that at such large distances between stations, much more detailed information may be obtained by studying the horizontal intensity than by studying the vertical intensity, and thinks that this results clearly from a study of the horizontal intensities in Figure 1, especially if it be realized that the anomalies are 3-dimensional.

The best information is of course obtained by a combination of the horizontal and the vertical intensities of a magnetic vector in space.

The Coast and Geodetic Survey has measured the declination and the horizontal and vertical intensities at the occupied stations. If the normal declination and the horizontal and vertical intensity be figured for each station and these normal values are deducted[3,4] from the actually measured values, the local deviation of the declination and the local vertical and south-north horizontal component of the total local magnetic vector are obtained as the difference. From the deviation of the declination may be easily figured also the local west-east component of the total local magnetic vector.

The average absolute accuracy of the components of these local magnetic vectors empirically lies at $\pm 40$ gammas, the average accuracy relative to neighboring stations at $\pm 20$ gammas.

The local magnetic vectors have been plotted at their respective stations on the maps of the principal oil-producing states, in the shape of vector triangles. The two dashed lines represent the horizontal and the vertical vectors; the hypotenuse is the total vector. If the vector triangle be turned through 90° around the horizontal vector, which is of course the dashed line beginning at the station point, the direction in space of the total vector may easily be visualized and the direction marked by a pin, if the map is mounted on cardboard.

[1] A. Nippoldt, *op. cit.*

[2] G. B. Somers, *op. cit.*

[3] A. Nippoldt, *op. cit.*

[4] L. A. Bauer, "Chief Results of a Preliminary Analysis of the Earth's Magnetic Field for 1922," *Terr. Mag.*, Vol. 28 (1923), pp. 1–28.

In studying these local vector maps, it should be considered that, as shown in Figure 1, there exists somewhere along the prolongation of the horizontal vector either a magnetic "high" or "low," which corresponds with some kind of geologic feature, either of structural or petrographic character.

The great and irregular variations of the total intensity and of the directions of most of the horizontal vectors should make it clear that most of these features necessarily must be localized.

This is the reason why no attempt has been made to connect the stations by certain curves, indicating, for example, equal total intensities, equal angles of inclination or equal vertical and horizontal intensities, though by help of the vectors the last two sets of curves could, of course, be much more intelligently computed than from the vertical or horizontal components alone.

A few of the regional geologic "structures" can be quantitatively interpreted by the help of these vectors.

Due to the long distances between stations, it has been necessary to use the most reasonable geological interpretation of the vector maps. Though two, three, or more local "highs" and "lows" are possible between two neighboring stations, it is probable that regional geologic "structures" extend at right angles to the horizontal magnetic components, where the majority of the latter are nearly parallel with one another over a large area, that is, a common geologic feature is probably responsible for a series of vectors, if they are all directed toward, or away from, the same point.

Due to the long distances between stations, the interpretation was mainly restricted to regional magnetic anomalies, though it is expected it will be found that the main value of the vector maps lies just in these areas, where the magnetic anomalies are so localized, or so shallow that no relation between the individual vectors can be established.

For all those areas where the vectors indicate regional magnetic tendencies, we may reasonably assume that the vectors are mainly due to deeply buried regional structure. But if the main magnetic influence in these areas originates at great depths and if the total intensity of the vectors amounts to only a few hundred gammas, we must conclude that the average magnetometer surveys can not possibly yield much information with regard to commercial structure, unless the deeper structure is truly reflected within the shallower beds. The results of the average magnetometer surveys are comparable with the

results which we would obtain with torsion balances, if their accuracy were reduced to $\pm 10$ Eötvös. If, however, the accuracy of the magnetometer surveys is greatly increased, these surveys may yield important information about structure at commercial depths also in these areas where the magnetic anomalies as located by the average magnetometer survey are unquestionably due to deeply buried regional structure.[1]

As the vectors are of sufficient accuracy, they allow a checking and tying-in of scattered magnetometer surveys. These stations should prove of the same value to 3-dimensional magnetometer surveys as pendulum stations to gravimetric surveys.

The vector maps show at a glance which areas are of interest for magnetometer surveys, what size anomalies may be expected, how far a magnetometer survey has to be extended or where it is best commenced to cover a certain anomaly.

In the following study of the vector maps no attempt has been made for an exhaustive interpretation of all vectors. The reader may easily perceive an abundance of further detailed information, which may interest him, especially in connection with scattered magnetometer surveys and detailed geologic information.

## LOUISIANA[2]

The vector map of this state (Fig. 2) gives a true picture of the known main structural trends and further indicates many distinct "structures."

*Sabine uplift.*—The horizontal components of the two negative vectors at Benton and Shreveport concur at a point about 10 miles southwest of Shreveport, at which point therefore a magnetic "high" is suggested. A line connecting this "high" with the "high" indicated a few miles south of Many coincides well with the axis of the Sabine uplift.

*North Louisiana geosyncline.*—The north Louisiana geosyncline is expressed by the negative vectors at Ruston, Jonesboro, and Winnfield.

[1] D. M. Collingwood, "Magnetics and Geology of Yoast Field, Bastrop County, Texas," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 9 (September, 1930), pp. 1191-97.
E. D. Lynton, "Some Results of Magnetometer Surveys in California," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 11 (November, 1931), pp. 1351-70.
A. Nippoldt, *Verwertung magnetischer Messungen zur Mutung* (Berlin, 1930), p. 58.

[2] The local magnetic vectors are based on the information given in "United States Magnetic Tables and Magnetic Charts for 1925," *op. cit.*

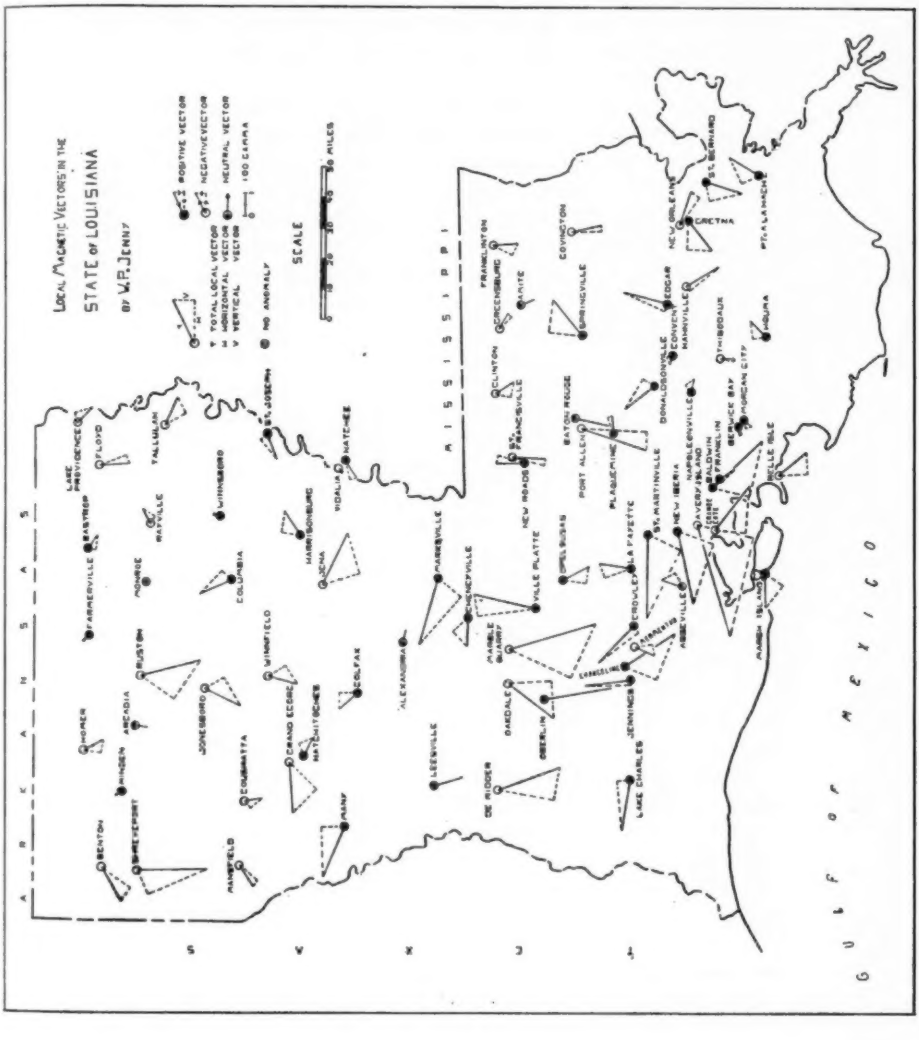

LOCAL MAGNETIC VECTORS IN THE
STATE OF LOUISIANA
BY V.P. JENNY
POSITIVE VECTOR
NEGATIVE VECTOR
NEUTRAL VECTOR
100 GAMMA
T TOTAL LOCAL VECTOR
H HORIZONTAL VECTOR
V VERTICAL VECTOR
NO ANOMALY
SCALE
MILES
ARKANSAS
MISSISSIPPI
TEXAS
GULF OF MEXICO

FIG. 2

*Area east of geosyncline.*—East of the geosyncline are found two trends of magnetic "highs," which parallel the axis of the Sabine uplift: (1) the Farmerville-Columbia-Harrisonburg trend and (2) the Bastrop-Winnsboro trend.

On the second trend lie the gas fields of Monroe and Richland. The magnetic "high" indicated slightly north of Bastrop is interpreted as an uplift in the deep basement rocks, which uplift accounts for the Monroe gas field. From magnetometer work we know that half way between Rayville and Winnsboro a similar magnetic "high" and corresponding uplift accounts for the Richland gas field.

The magnetic "high" as indicated south of Winnsboro therefore suggests other possibilities of uplifts along the known trend toward the south.

*Central Louisiana.*—A magnetic "high" south of Colfax is indicated.

The concurrence of the horizontal vectors of Jena, Alexandria, and Marksville at a point about 10 miles northeast of Marksville suggests a magnetic and possibly structural "high" of large dimensions at that point.

Other magnetic "highs" are suggested between Leesville and De Ridder and southeast of Cheneyville.

At St. Francisville and New Roads there is a striking example of two stations which may reasonably be assumed to lie on the same "structure." The magnetic lines of force come out of the ground at a low angle at St. Francisville, assume a horizontal direction between the two stations, and penetrate into the ground at a low angle at New Roads, directed toward a magnetically positive "structure" on the south.

The distances are too great to say that this "structure" is the eastern extension of a west-east ridge or anticline as indicated between Ville Platte and Opelousas, but this possibility is strongly suggested.

*Southern Louisiana.*—There is a northwesterly trend of magnetic "highs" from Morgan City to St. Martinsville; this trend parallels a line through the Five Island domes, about 20 miles west, and may correspond with the so-called Iberian structural axis.

No continuation of this trend beyond St. Martinsville can be preceived from the vectors. An east-west trend of magnetic "highs" from St. Martinsville to Lake Charles, however, is clearly noticeable. This trend passes south of Lafayette, northeast of Crowley, north

of Evangeline, south of Lake Charles, and corresponds with the well known structural axis in southern Louisiana along which, besides several unproved prospects, lie the domes and oil fields of Jennings, Roanoke, Welsh, and Iowa. The indicated "high" south of Lake Charles suggests the conclusion which has been drawn from recent seismograph work in this area, that the structural axis turns southward past the Iowa dome and continues south of Lake Charles toward the Lockport dome.

The large negative vectors at DeRidder, Oakdale, and Marble Quarry and the horizontal vector at Oberlin suggest a west-east magnetic "high" trend south of Oberlin. Due to the large intensity of these vectors, it does not seem justifiable to connect them with the magnetic "high" trend of Lafayette-Lake Charles but it may be concluded that the magnetic "high" or anticlinal structure indicated between Ville Platte and Opelousas extends westerly past the Texas border. A corresponding gravimetric high trend is indicated by torsion-balance work and is usually interpreted as due to a deep petrographic or structural regional feature.

## TEXAS[1]

### REGIONAL STRUCTURE

*Delaware basin.*—The magnetic center of the Delaware basin seems to lie between Pecos and Barstow. The negative vector at Pecos is directed toward the west, and at Barstow, toward the east or toward the Central Basin platform, which is indicated by the positive vector at Monahans.

*Main Permian basin.*—In the southwest part of the main Permian basin the negative vectors from Odessa to Big Springs are directed toward the southeast, and the negative vectors at Andrews and Lamesa toward the northwest, which means that the magnetic axis of a basin lies between these two sets of stations.

*The Bend arch.*—The Bend arch is indicated by the positive vectors at Brownwood and neighboring stations, with a north extension to Jacksboro.

*Central Mineral region.*—The horizontal components of the positive vectors at Llano and Burnet and the neutral vector at Lampasas all concur at a point half-way between these three stations. This

[1] The local magnetic vectors are based on the information given in "United States Magnetic Tables and Magnetic Charts for 1925," *op. cit.*

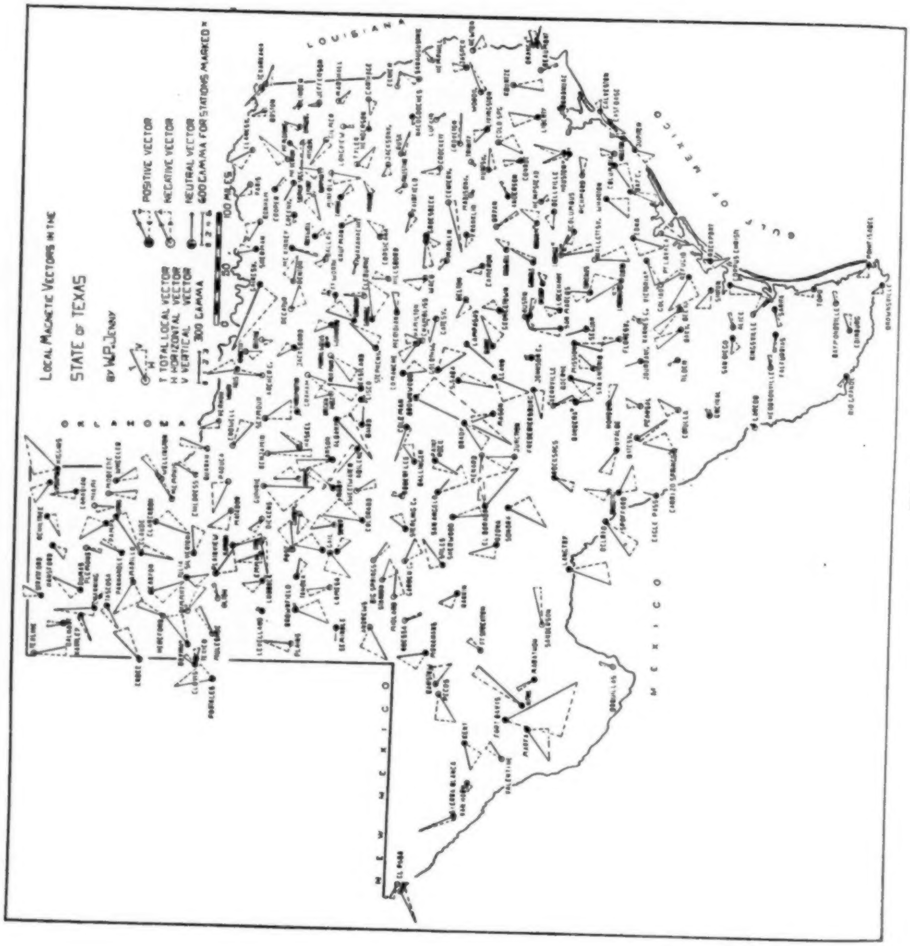

LOCAL MAGNETIC VECTORS IN THE
STATE OF TEXAS
BY W.P.JENNY
T TOTAL LOCAL VECTOR
H HORIZONTAL VECTOR
V VERTICAL VECTOR
300 GAMMA
POSITIVE VECTOR
NEGATIVE VECTOR
NEUTRAL VECTOR
600 GAMMA FOR STATIONS MARKED
100 MILES
LOUISIANA
GULF OF MEXICO
MEXICO
NEW MEXICO
OKLAHOMA

FIG. 3

point should correspond with the center of a large magnetic "high," due to the Llano-Burnet uplift.

*East Texas syncline.*—The East Texas syncline is indicated by many negative vectors in the northeastern part of the state.

*Northwest Texas.*—A basin of considerable extent is indicated in northwest Texas, with its magnetic center half-way between Hereford, Dimmitt, and Bovina. The rim of this basin probably extends from Bovina northward toward Endee, eastward and southward toward Canyon, Tulia, and Plainview, and westward north of Olton and Muleshoe back to Bovina. This basin may hold oil possibilities similar to the Delaware or Black Shale basins.

*Gulf Coast.*—Many of the horizontal magnetic components along the Gulf Coast are nearly perpendicular to the coast; we may therefore expect regional "structures" parallel with the coast.

Especially in southwest Texas such "structures" seem to be clearly indicated. We may further follow up the regional magnetic high trend between Ville Platte and Opelousas, as discussed in the last paragraph on "Louisiana," south of Newton, Woodville, Cold Spring, Conroe, Hempstead, Bellville, Columbus. This trend may prove of interest in the light of recent developments south of Conroe.

### LOCAL STRUCTURE

Anticlinal structure at Big Lake is indicated by a positive vector at Rankin and at Stiles.

A southwest-northeast ridge is indicated by the positive vectors at Sherwood and San Angelo.

A magnetic "high" is indicated between Ozona, Eldorado, and Sonora. With this "high" may correspond one "structure" or more, which, in the light of recent development west of Ozona, may prove of great interest.

The great variety in the magnetic field along the coast should prove that magnetometer surveys there may be not only of a regional, but also of a local, structural interest in many places.

The Refugio anticline and the Pierce-Junction and the Liberty domes are indicated by positive vectors.

It is possible that these magnetic "highs" are the result of the uplifted strata at relatively shallow depths, though the possibility also exists that they are due to uplifts in the basement. In any case, more detailed magnetic investigations may prove of great value, especially in southwest Texas.

ARKANSAS[1]

Arkansas has been divided into four main geological sections: (1) the Gulf Coastal Plain, south and east of a line passing through DeQueen, Arkadelphia, Little Rock, and Pocahontas; (2) the Arkansas Valley, between a line from Van Buren to Heber Springs on the north and a line from Waldron to Little Rock on the south; (3) the Ouachita Mountain region, between the Arkansas Valley and the Gulf Coastal Plain; (4) and the Ozark region, north of the Arkansas Valley.

*Gulf Coastal Plain.*—The southern part of the Gulf Coastal Plain from DeQueen to Lake Village is indicated as a large negative anomaly, interrupted by a north-south trend of magnetic "highs" from Hamburg to Star City, which seems to be the northward continuation of the magnetic high trend from Winnsboro to Bastrop in Louisiana.

The well known local anomaly at Rison is due to peridotite intrusions with as much as 20 per cent magnetite content.

The positive vectors from Stuttgart to Forest City seem to belong to a large northwest-southeast magnetic high trend, toward which are also directed the negative vectors at Wynne and Helena. The large irregular positive and negative vectors farther north suggest very localized and relatively shallow sources of magnetism.

*Ouachita Mountain region.*—In the Ouachita Mountain region it is interesting to note that the two positive vectors at Mena and Mount Ida are almost horizontal and directed toward the Arkansas Valley, instead of south toward the axis of the Ouachita Mountains, as would be expected if the Ouachita Mountains were the result of uplift in the Basement complex.

If it be assumed that the Basement complex is the cause of the magnetic anomalies in this region, the magnetic conditions suggest that this complex lies deeper below the Ouachita Mountains than below the Arkansas Valley, because the magnetic lines of force seem to come out of the ground at DeQueen and Murfreesboro, to assume a horizontal direction over the mountain range, and to penetrate into the ground in the Arkansas Valley.

Thus the magnetic conditions seem to be in favor of the theory that the Ouachita Mountains are the result of a huge overthrust, as explained by W. A. J. M. van Watershoot van der Gracht.[2] Similar

[1] The local magnetic vectors are based on the information given in "United States Magnetic Tables and Magnetic Charts for 1925," *op. cit.*

[2] W. A. J. M. van Watershoot van der Gracht, "Permo-Carboniferous Orogeny in South-Central United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 9 (September, 1931), pp. 991–1057.

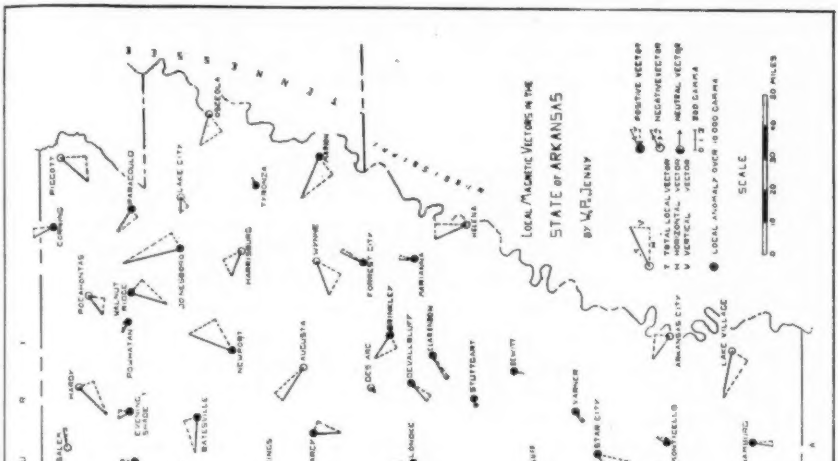

LOCAL MAGNETIC VECTORS IN THE
STATE OF ARKANSAS
BY V.P. JENNY
SCALE
MISSOURI
OKLAHOMA
TEXAS
LOUISIANA
LITTLE ROCK
HOT SPRINGS
PINE BLUFF
EL DORADO
FORT SMITH
HELENA


FIG. 4

magnetic conditions exist in the region of the nappes of the European Alps.

*Arkansas Valley and Ozark Mountain regions.*—The magnetically positive zones of the Arkansas Valley and Ozark Mountain regions are separated by a negative zone extending from Fayetteville to Marshall.

## OKLAHOMA[1]

*Eastern Oklahoma.*—In eastern Oklahoma is to be observed the same arrangement of the magnetic anomalies as in western Arkansas; that is, the positive vector at Miami is indicative of the Ozark Mountains, the negative vectors near Westville are indicative of the magnetic "low" between the Ozark uplift and the Arkansas Valley, which latter "structure" is represented by the positive vectors at Sallisaw, Muskogee, Stigler, and Poteau.

The few stations in the general area of the Ouachita Mountains seem to confirm the interpretation given for the magnetic anomaly in the Ouachita region of Arkansas.

On the basis of the west-east direction of the horizontal magnetic components, it seems possible to follow a positive magnetic trend from Nowata to Pryor and a second trend from Bartlesville through Tulsa, Sapulpa, and Okemah to Holdenville, along which trends lie the main oil "structures" of northern Oklahoma.

*Arbuckle Mountains.*—The Arbuckle Mountains are indicated by a strong positive vector at Tishomingo. The positive vector at Durant might indicate the axis of the Arbuckle Mountains as extending southeast and northwest.

*Wichita Mountains.*—The Wichita Mountains lie along a magnetic high trend beginning at Marietta and passing north of Waurika, Walters, and Hobart to Sayre. The oil fields of southern Oklahoma lie along this line.

A magnetic high trend is indicated between Sulphur and Oklahoma City.

Another high trend lies east of Rush Springs, Chickasha, and Minco.

Another possible high trend lies between Alva and Carmen, between Trail and Taloga, and east of Hammon.

The southern extension of the Nemaha mountains might be indicated by the positive vectors at Medford, Pond Creek, and Enid.

[1] The local magnetic vectors are based on the information given in "United States Magnetic Tables and Magnetic Charts for 1925," *op. cit.*

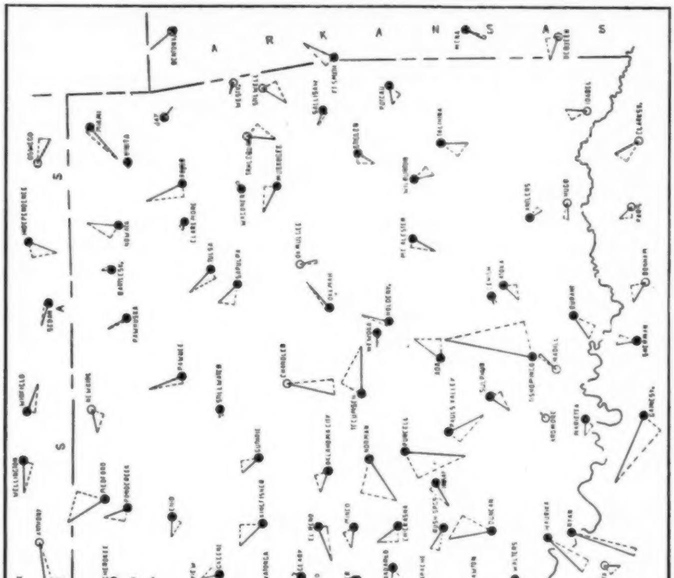

LOCAL MAGNETIC VECTORS IN THE
STATE OF OKLAHOMA
BY W.P.JENNY
T TOTAL LOCAL VECTOR
H HORIZONTAL VECTOR
V VERTICAL VECTOR
POSITIVE VECTOR
NEGATIVE VECTOR
NEUTRAL VECTOR
400 GAMMA
SCALE
0
50
100 MILES
ARKANSAS
KANSAS
TEXAS

FIG. 5

## KANSAS[1]

*Nemaha Granite ridge.*—The outstanding feature of eastern Kansas is the Nemaha Granite ridge, which extends from Seneca in a southwesterly direction toward Winfield. The top of the granite lies at +560 feet near Seneca and at −2,200 feet near Winfield, which indicates a southward dip of the ridge. From the *Kansas State Geological Survey Bulletin 13* we quote:

> The earth movement, which elevated the granite appears to have taken place in the post-Mississippian and pre-Pennsylvanian time, for the upper part of the Ordovician and all of the Mississippian has been stripped away in the region of Eldorado and Augusta. North of Butler County, along the axis of the uplift, all of the sedimentary rocks older than the Pennsylvanian were removed so that the Pennsylvanian rests directly on the granite ridge.

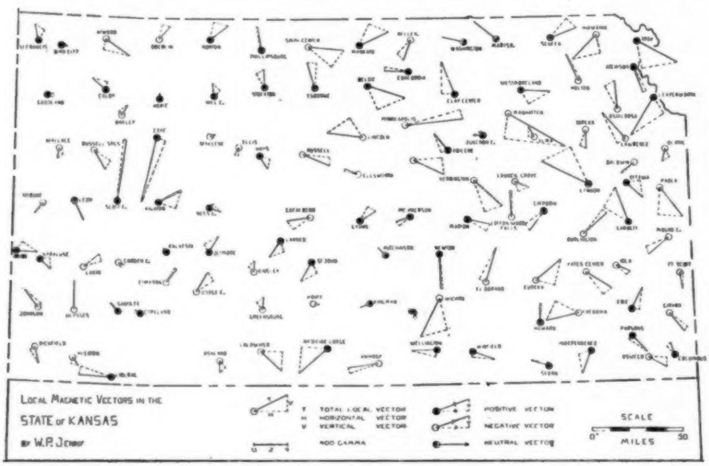



FIG. 6

If, therefore, the granite is embedded in lower Ordovician in the southern part of the ridge and in the Pennsylvanian in the northern part, we may expect this ridge to be indicated magnetically as a "low" on the south and as a "high" on the north if the Ordovician is of a higher and the Pennsylvanian of a lower magnetic permeability than the granite.

[1] The local magnetic vectors are based on the information given in "United States Magnetic Tables and Magnetic Charts for 1925," *op. cit.*

But, though in central and western Kansas magnetic "lows" seem actually to correspond in some places with structural "highs," the vector map seems to be in favor of the assumption that in the eastern part of the state magnetic "lows" correspond with structural "lows," and magnetic "highs" with structural "highs."

The axis of the Nemaha ridge lies slightly east of Seneca, 5 miles west of Alma and Council Grove, slightly west of Cottonwood Falls and Eldorado, and between Winfield and Wellington. The ridge has a very steep eastern flank but slopes much more gently toward the west. Thus, the center of mass of the ridge lies considerably west of the structural axis, which would explain a corresponding shift of the magnetic axis.

We think that the axis of the ridge is indicated by the positive vectors at Seneca, Council Grove, and Winfield-Wellington, and by the negative vectors at Alma and Eldorado, both of which point toward the west, so that the magnetic lines of force, emerging at Alma and Eldorado, may enter the positive ridge a few miles west of the stations.

Drilling has revealed a structural low trend along the east flank of the ridge and another extended "low," with a west-east axis, between Eureka-Emporia and Yates Center-Burlington. The first trend is indicated magnetically by the negative vectors at Hiawatha, Holton, Alma, and Eldorado. In the second trend, it is clear that the negative vectors at Eureka, Yates Center, Iola, Burlington, Cottonwood Falls, and the positive vector at Emporia may all be assumed to emerge from the same magnetic "low."

We have pointed out already that in central and western Kansas both magnetic "lows" and "highs" may correspond with structural "highs."

The large and irregular vectors should yield considerable information, if the vector map is combined with magnetometer surveys and detail geologic maps.

### MISSISSIPPI[1]

Many of the magnetic horizontal components of the vectors in the northern half of Mississippi have a northeast or a southwest direction, which may indicate a general northwest-southeasterly trend of the deeper "structure." We might suspect two magnetic high trends: (1) Butler-Philadelphia-Kosciusko-Greenwood-Rosedale on the south and

[1] The local magnetic vectors are based on the information given in "United States Magnetic Tables and Magnetic Charts for 1925," *op. cit.*

(2) Carrollton-Columbus-Pittsboro-Water Valley, between Helena and Tunica on the north, and interpret them as indicative of the generally assumed connection of the Appalachian with the Ouachita Moun-

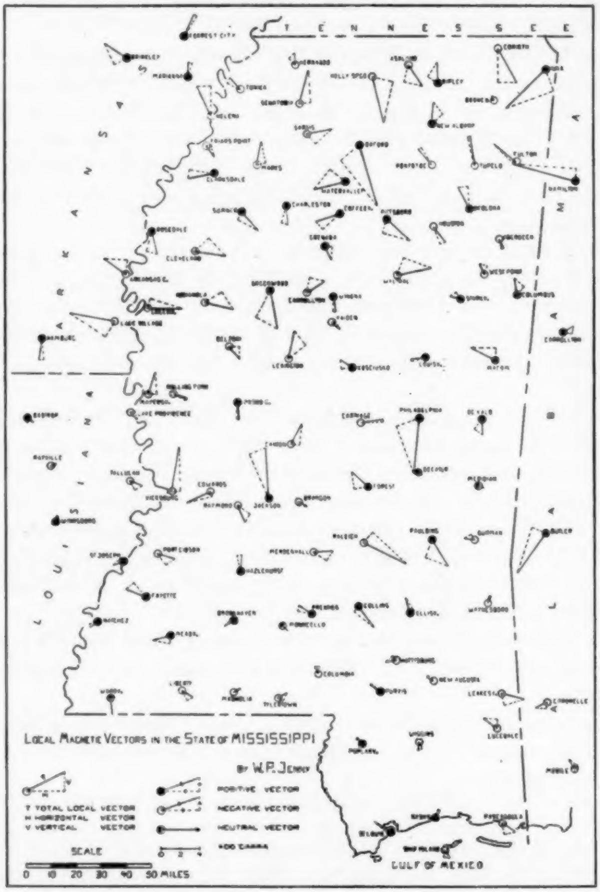



FIG. 7

tains. The distances between the vectors and their irregularities are, however, too great to allow any definite statement, without additional magnetic and geologic data.

The positive vector at Jackson indicates a magnetic "high" slightly southeast of the town. This "high" is due to an igneous plug, supposedly nepheline-syenite, and is in agreement with magnetometer surveys of the well known gas field. An interesting west-east trend of magnetic "highs" extends from Fayette to Ellisville.

In general, there are hardly more than two vectors in Mississippi, which can be definitely attributed to the same structure. This circumstance may be interpreted as due to local and relatively shallow sources of magnetism, which should be favorable for detailed investigations by the magnetometer.

### ALABAMA[1]

From the northeastern corner of Alabama, a magnetic high trend, extending southwest to Greensboro, indicates the southern extension of the Appalachian Mountains.

The vectors of the stations surrounding Greensboro are all positive and indicate by their direction that a large continuous positive anomaly exists, covering that part of the state, which is explained as the "southernmost tip of the folded Appalachian Mountains" by D. R. Semmes.[2]

This "high" is an example of a large magnetic anomaly, corresponding with an extended structural feature, which could be correctly interpreted by the study of the vertical intensity alone.[3]

Another outstanding feature is the "low" at Wetumpka. This "low" may lie along a low trend Center-Anniston-Talladega-Rockford-Wetumpka, with the high trend Guntersville-Greensboro on the west and another high trend on the east, which would pass near Ashland, Dadeville, and between Tuskegee and Wetumpka.

In the southern part of the state a low trend is indicated between Georgiana and Greenville, extending northwestward toward Camden and southeastward toward Elba. Another possible low trend lies east of Tuskegee, Union Springs, and Troy.

The positive vectors at Opp, Geneva, and possibly also at Ozark and Abbeville appear to be due to localized "structures," which might be of interest for oil and gas possibilities, because they lie in the Gulf Coastal belt.

[1] The local magnetic vectors are based on the information given in "United States Magnetic Tables and Magnetic Charts for 1925," *op. cit.*

[2] D. R. Semmes, *Geol. Survey of Alabama Bull. 22.*

[3] L. Spraragen, *op. cit.*

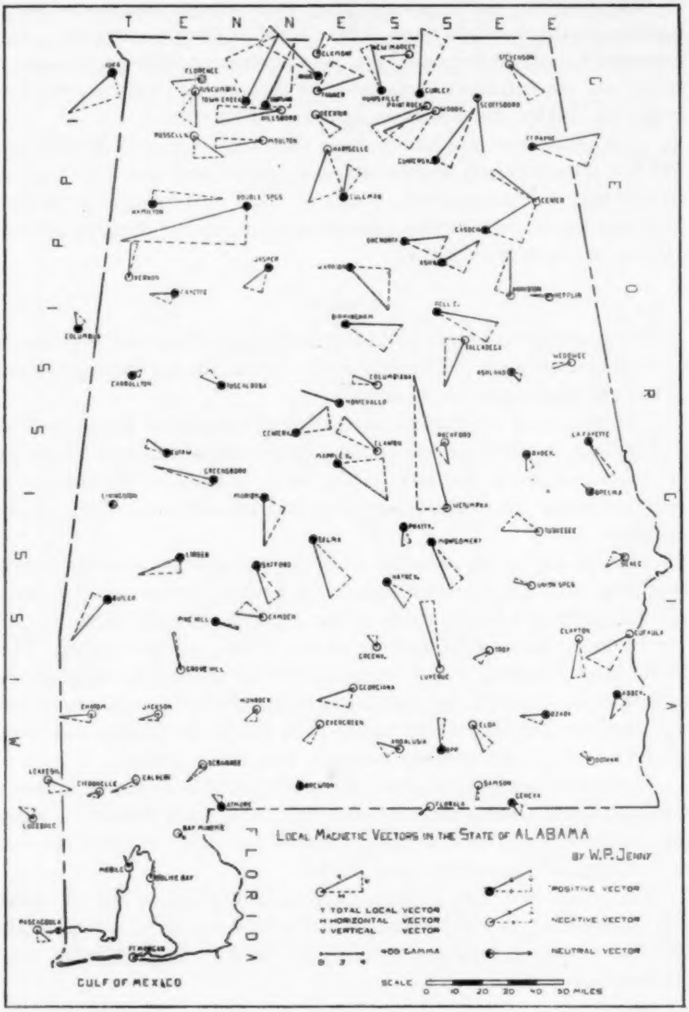

TENNESSEE
MISSISSIPPI
GEORGIA
FLORIDA
GULF OF MEXICO
LOCAL MAGNETIC VECTORS IN THE STATE OF ALABAMA
BY W.P. JENNY
T TOTAL LOCAL VECTOR
H HORIZONTAL VECTOR
V VERTICAL VECTOR
400 GAMMA
POSITIVE VECTOR
NEGATIVE VECTOR
NEUTRAL VECTOR
SCALE
0 10 20 30 40 50 MILES

FIG. 8

An interesting feature is the indicated high trend between D'Olive Bay-Mobile-Lucedale on the south and Bay Minette-Citronelle-Leakesville on the north. This trend is parallel with the Hatchetigbee anticline, about 50 miles farther north.

The Hatchetigbee anticline is not indicated by the vectors, because the stations are not favorably located. It is parallel with another magnetic high trend about 30 miles farther north, extending from Butler toward midway between Grove Hill and Pine Hill. This last trend is known from magnetometer work in combination with the vector map.

It seems, therefore, that there are three parallel pronounced anticlinal trends, south of, and practically at right angles to, the Appalachian trend from Guntersville to Greensboro.

In the writer's opinion, the three anticlinal trends in southwestern Alabama represent a mountain system distinctly different from the Appalachians. If the Appalachians extend farther than Greensboro and Linden, they are expected to disappear below the anticlinal trend at Butler. It is further suggested that the three anticlinal trends in southwestern Alabama possibly represent an eastern extension of the Ouachita Mountain system, inasmuch as the high trend at Butler might be followed through Philadelphia-Koskiusko-Greenwood-Rosedale into the Ouachita Mountains, and the high trend at Mobile through Ellisville-Fayette-Winnsboro-Bastrop-Hamburg-Star City.

In the northern part of Alabama we observe a pronounced magnetic high trend Hamilton-Double Springs-Cullman. This trend seems to join the high trend Guntersville-Greenboro, and to extend eastward between Stevenson and Fort Payne. In the writer's opinion, the trend north of Fort Payne to Hamilton is representative of the main Appalachian trend, whereas the trend Guntersville-Greensboro is a southwestward extension, branching off the main trend at Guntersville.

A possible westward continuation of the main trend of the Appalachians seems obscured by the magnetic influence of the Cincinnati uplift, which is indicated in the northeastern corner of Mississippi by the "high" at Iuka. On the basis of magnetics only, we might suspect a high trend from Oxford toward a location midway between Helena and Tunica, with a westward continuation toward Brinkley and the Arkansas Valley. A continuation of the Arkansas Valley magnetic high trend into Oklahoma might be suspected south of Muskogee-Guthrie-Kingfisher-Watonga.

Additional magnetic and geologic information is needed, however, to clear up the possible existence and geologic meaning of this suspected trend.

### CALIFORNIA[1]

It seems probable that the main magnetic effects in California are due to deep regional structure with a northwest-southeasterly trend. This interpretation explains the southwest and northeast directions of the most of the horizontal components, and is well established by the known regional geology.

A magnetic high trend extends all along the California Valley from Red Bluff in the north through Stockton to Bakersfield in the south.

A second parallel high trend may be noticed east of Bradley, San Lucas, Soledad, and Salinas.

Farther south it seems possible to construct a high trend from Oceanside to Santa Monica and another parallel trend from San Clemente to San Nicholas.

The magnetic stations are considerably denser in the valleys than in the mountainous regions of the Sierra Nevada and Coast Ranges or in the Mojave Desert. Inasmuch as the valleys represent sedimentary basins, whereas the mountainous regions are mainly composed of volcanic rocks, schists, gneisses, and highly metamorphosed sediments, it is surprising to note that the average vector in the valleys is of about the same magnitude as the average vector in the mountainous regions. This circumstance may no doubt be explained in part by the geographic location and distribution of the stations, but it may possibly also have a deeper meaning, which the writer will try to explain.

If the magnetic field is due to regional "structures" and if the cross sections in Figure 2 of "Decline of Great Basin"[2] are true, we should logically expect a magnetic high trend about 20 or 30 miles west of the San Andreas fault, over the Santa Lucia "blocks," another high trend over the Sierra Nevada "block," and a low trend in the California Valley, or sedimentary basin, between these two "blocks."

The cross section mentioned passes approximately through Soledad and slightly north of Madera, on our vector map. We notice a considerable difference between the actual magnetic data and those that would be assumed if based on the cross section.

[1] The local magnetic vectors are based on the information given in "United States Magnetic Tables and Magnetic Charts for 1925," *op. cit.*

[2] J. Edmund Eaton, "Decline of Great Basin, Southwestern United States," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 16, No. 1 (January, 1932), p. 5.

The magnetic high trend indicated between Salinas and Hollister lies approximately along the San Andreas fault, that is, along the east flank of the Santa Lucia "blocks," and the high trend in the California


FIG. 9

Valley, a few miles northeast of Mendota, practically lies above the western edge of the Sierra Nevada "block," as shown in the figure mentioned.

There are not enough stations on the Sierra Nevada or Santa Lucia "blocks" to make possible any definite statement regarding

their magnetic behavior. From the magnetic vectors at Bradley, San Lucas, Soledad, and Salinas it seems, however, permissible to conclude that the Santa Lucia "blocks" would act somewhat neutral magnetically. If this should be the fact, then these "blocks" could not possibly reach great depths.

It is interesting to note that the two pronounced magnetic high trends occur where they are least expected, that is, along the east flank of the Santa Lucia "blocks" and along the west flank of the Sierra Nevada "block." If we interpret these high trends in the usual way, we should expect an anticlinal trend in the Basement complex below the California Valley, or along the west edge of the Sierra Nevada "block," and another anticlinal trend in the Basement complex approximately below the San Andreas fault, or along the east edge of the Santa Lucia "blocks."

To interpret the magnetic data properly, we have to assume that the Santa Lucia "blocks" and the Sierra Nevada "block" are floating on a Basement complex, which is greatly depressed below the "blocks" and elevated along the edges of the "blocks." This might be explained either by assuming that these two "blocks" are laccoliths, or by the assumption of huge overthrusts.

The mechanics of the "progressive breaking down of the crystalline Pacific borderland," as explained by the arrows in Figure 2 and in the text of "Decline of Great Basin,"[1] are not sufficiently free from possible objections, to speak plainly against the foregoing interpretation.[2]

In connection with a detail geologic map and scattered magnetometer surveys, the vector map of California may prove of value also for the study of local anomalies.

### SUMMARY OF REGIONAL ANOMALIES

Figure 10 summarizes the regional magnetic trends and areas of magnetic anomalies, which have been mentioned before in the discussion of the respective states. We have discriminated between probable and possible anomalies. The probable anomalies are fairly well established by the magnetic vectors; the possible anomalies, however, may upon more detailed investigations prove to be more localized and not as continuous as shown on the map, though the vectors

[1] J. Edmund Eaton, *op. cit.*

[2] Friedrich Noelke, "Geotektonische Hypothesen," *Sammlung geophysikalischer Schriften*, No. 2 (Berlin, 1924), p. 70, b.

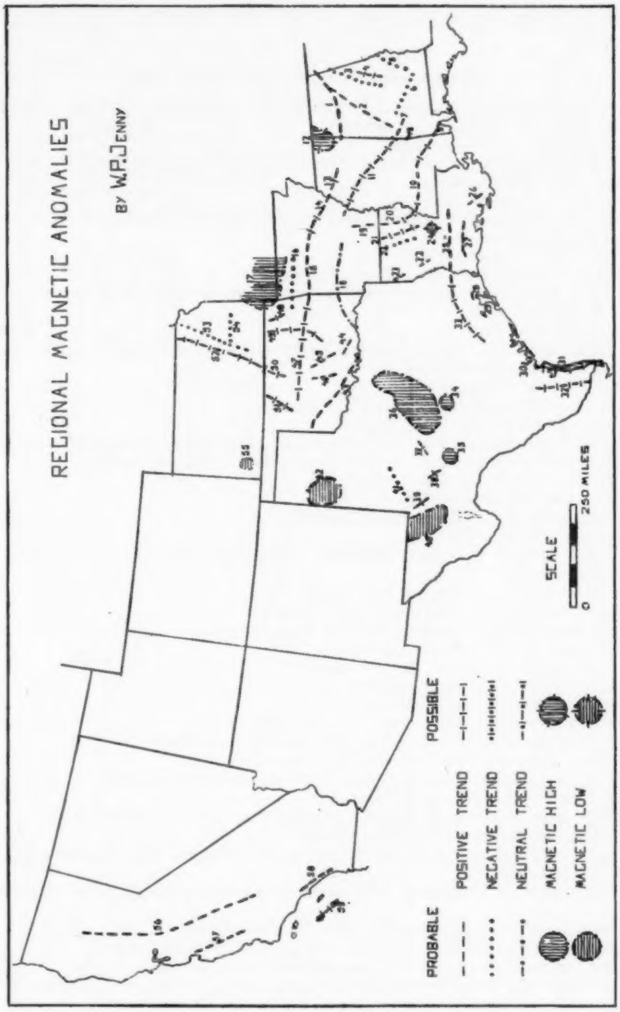

REGIONAL MAGNETIC ANOMALIES
BY W.P.JENNY
PROBABLE
POSSIBLE
POSITIVE TREND
NEGATIVE TREND
NEUTRAL TREND
MAGNETIC HIGH
MAGNETIC LOW
SCALE
0
250 MILES

FIG. 10

so far computed seem to be in favor of continuous trends, or at least do not disprove the trends based on regional magnetic or geologic evidence.

LIST OF REGIONAL ANOMALIES (FIG. 10)

1. High trend beginning between Stevenson and Ft. Payne and extending to Hamilton
2. High trend Guntersville-Greensboro
3. Low trend Center-Wetumpka
4. High trend Ashland to a location between Tuskegee and Wetumpka
5. Low trend Tuskegee-Troy
6. Low trend Camden-Elba
7. High trend Butler to a location between Grove Hill and Pine Hill
8. Hatchetigbee anticline
9. High trend north of Mobile
10. Trend of "highs" from Ellisville to Fayette
11. Possible high trend Butler-Philadelphia-Greenwood-north of Rosedale-between De Witt and Varner
12. High area near Iuka
13. Possible high trend Oxford, Water Valley to a location between Helena and Tunica
14. High trend Marianna-Brinkley
15. High trend of Arkansas Valley
16. Low trend Marshall-Fayetteville-Tahlequah
17. "High" at Miami and Ozark region
18. Neutral trend parallel with axis of Ouachita Mountains from area between Hugo and Antlers toward area south of Mena and Mount Ida to Sheridan
19. High trend Hamburg-Star City
20. High trend Winnsboro-Bastrop
21. Possible high trend Farmerville-Harrisonburg
22. Low trend Ruston-Winfield
23. "Highs" south of Shreveport and Many, with connecting trends parallel with axis of Sabine uplift
24. Possible "high" northeast of Marksville
25. High trend between Ville Platte and Opelousas
26. High trend between Morgan City and Napoleonville
27. High trend Lafayette-Lake Charles
28. "High" south of Liberty, regional trend
29. "High" south of Houston, regional trend
30. "High" at Refugio, regional trend
31. Possible high trend Point Isabel-Corpus Christi
32. Possible high trend east of Edinburgh-Falfurias-San Diego
33. Possible high trend south of Newton-Conroe-Columbus
34. "High" at Lampasas, Llano, Burnet, corresponding with the Llano-Burnet uplift
35. "High" at Sonora, Ozona, Eldorado
36. "High" from Brady to Jacksboro, corresponding with the Bend arch
37. Possible high trend north of San Angelo
38. "High" indicated by the vectors at Rankin and Stiles, probably corresponding with the Big Lake anticline
39. "High" south of Monahans, with trend corresponding with Central Basin platform
40. "Low" near Pecos, corresponding with Delaware basin
41. Low trend, corresponding with the axis of main Permian basin
42. "Low" between Bovina, Tulia, Canyon, interpreted as basin
43. High trend Marietta-Lawton-Hobart-Sayre, corresponding with Wichita Mountains
44. High trend Tishomingo-Durant, corresponding with Arbuckle Mountains
45. High trend Sulphur-Oklahoma City
46. High trend Rush Springs-Minco
47. Possible high trend Fort Smith-Muskogee-Watonga

48. Possible high trend Nowata-Pryor
49. Possible high trend Bartlesville-Tulsa-Holdenville
50. Possible high trend east of Medford-Enid, corresponding with possible south extension of Nemaha Mountains
51. Possible high trend east of Alva-Trail
52. Possible high trend corsponding with Nemaha Mountains
53. Low trend east of Nemaha Mountains
54. Low trend between Yates center and Burlington
55. "Low" at Ulysses
56. High trend along California Valley
57. High trend along Salinas Valley
58. High trend from Oceanside to Santa Monica
59. Possible high trend San Clemente-San Nicholas

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1204-1211, 4 FIGS.

# APPLICATION OF REFLECTION SEISMOGRAPH[1]

EUGENE McDERMOTT[2]
Dallas, Texas

## ABSTRACT

This paper describes in detail a reflection seismograph survey of western Henderson and eastern Navarro counties, and covers the area just north of the Mexia-Powell oil field. A number of faults are located and closure is indicated on two. A cross section of the area shows the relation of the reflection records to the subsurface structure. Reflections were obtained throughout the area on the Pecan Gap and a basal member of the Austin chalk. Contour maps on these two reflection horizons are included.

## INTRODUCTION

The area surveyed in this application of the reflection seismograph lies just north of the Mexia-Powell fault-line fields in eastern Navarro and western Henderson counties, Texas, and has long been considered a favorable area in which to explore for a possible extension of this line of fields. At least twenty dry holes have been drilled in this area. A seismograph survey such as the one under consideration would have made possible the selection of the best location, structurally, so that one, or at most two, wells would have thoroughly tested the area for the presence of oil.

A total of approximately seventy-five depth determinations were made in a period of about two weeks, resulting in a cost per acre of somewhat less than 10 cents.

The author has attempted to present the data in the form of two contour maps, one of the top of the Pecan Gap chalk and the other of the basal member of the Austin chalk, a cross section with corresponding reflection records from which the depths to these two reflecting horizons were made, an enlarged view of a typical record showing the relation between the reflection events and the section, and has endeavored to make these as nearly self-explanatory as possible.

[1] Presented before the Association at the Oklahoma City meeting, March 25, 1932. Manuscript received, June 4, 1932.

[2] Geophysical Service, Inc., 1311 Republic Bank Building.

## PROCEDURE

As the trend of any faults that might exist was assumed to be the same as that of the field on the south, east-to-west lines of depth determinations were laid out, taking advantage of roads available. When the data indicated the presence of a fault, the layout was changed so as to increase the density of shot locations in the neighborhood of the fault and follow its trend. The program was essentially of a reconnaissance nature.

## CORRELATION OF REFLECTIONS

Two dominant reflections appear on the records. The interval between them corresponds to that between the top of the Pecan Gap chalk and the basal Austin. A standard Cretaceous velocity chart was used in the computation of the depth determinations. Although this could not be expected to give correct absolute depths beyond approximately 100 feet, as it was constructed from well determinations in another part of East Texas, interval and relative-depth determinations made from it could be relied upon to be correct to 0.5 per cent. The two contour maps show the interval between the Pecan Gap and the Austin to be approximately constant but indicate some regional variation.

A typical reflection record showing the relation of the reflection events to the geologic section is shown in Figure 1. The fact that a dominant reflection is obtained from near the base of the Austin chalk would indicate that the basal member of this body of chalk is considerably harder than the rest of the chalk section. Occasionally a reflection is obtained from the upper part of the chalk section, but it is never as pronounced as the basal reflection nor does it appear on the records with any regularity. In view of the dominant character of the two reflections and the regularity of interval between them, the possibility of miscorrelation is extremely small.

The two contour maps, Figures 2 and 3, were constructed from reflection depth determinations entirely. No well data were used. Although the contour maps may not check similar maps made from well data in absolute value, they should check as regards relative data. Most of the wells drilled in this area are shown on the contour maps.

A cross section showing two faults is presented in Figure 4. This cross section is along line *AA* indicated on the contour maps. The reflection records from which the depth determinations were made are shown opposite the cross sections. Each record corresponds with the

depth determinations opposite it on the cross section. The two reflections, Pecan Gap and basal Austin member, are marked on the records and the datum values shown. These datum values are shown to scale on the cross section.

Due to the greater depth of the Austin, the reflection from it should be smaller in amplitude than that from the Pecan Gap. For a reasonably large Pecan Gap reflection the Austin reflection amplitude

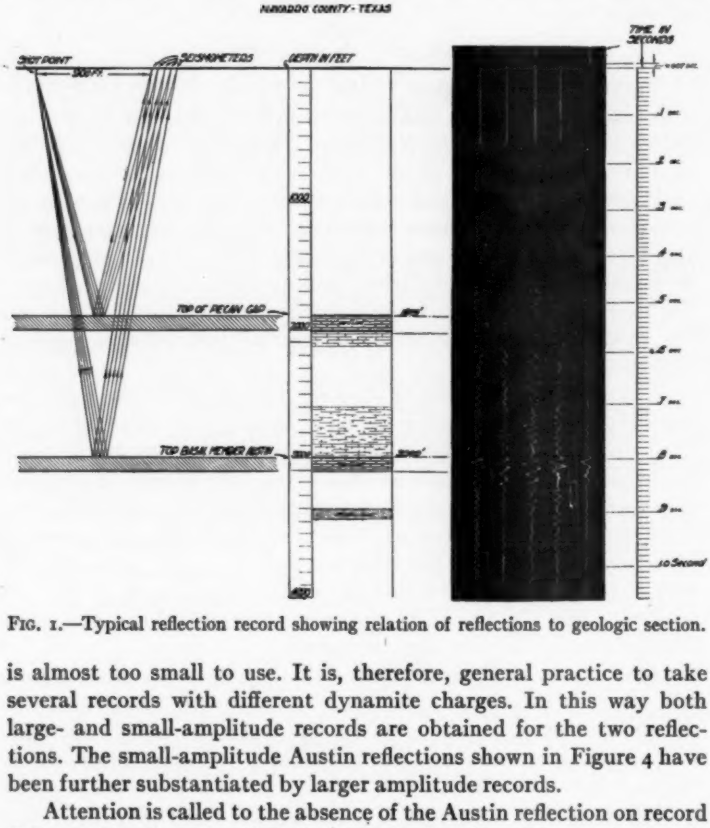



FIG. 1.—Typical reflection record showing relation of reflections to geologic section.

is almost too small to use. It is, therefore, general practice to take several records with different dynamite charges. In this way both large- and small-amplitude records are obtained for the two reflections. The small-amplitude Austin reflections shown in Figure 4 have been further substantiated by larger amplitude records.

Attention is called to the absence of the Austin reflection on record F.P.210. It so happens that the normal reflection point on the Austin falls in the Austin fault plane. In view of the extraneous disturbance in this record at the time of normal occurrence of the Austin reflec-

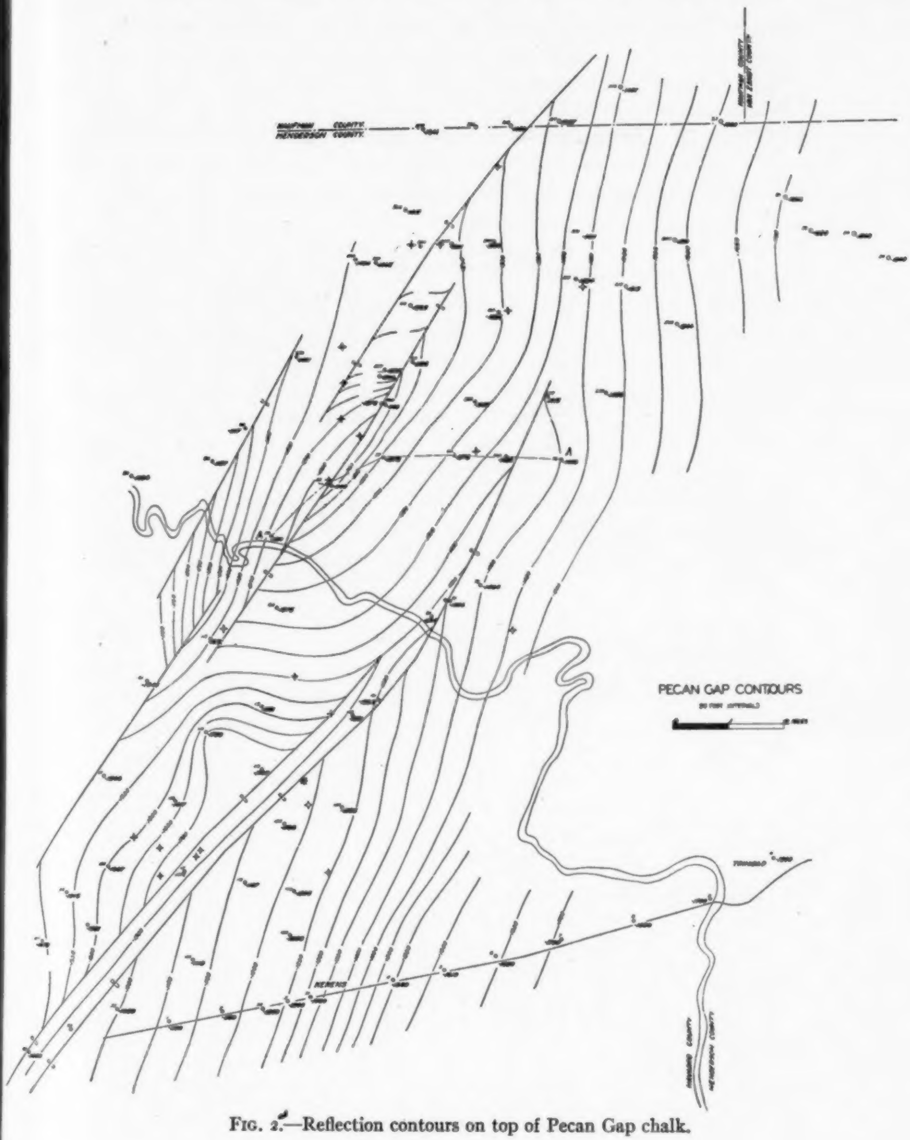



Fig. 2.—Reflection contours on top of Pecan Gap chalk.

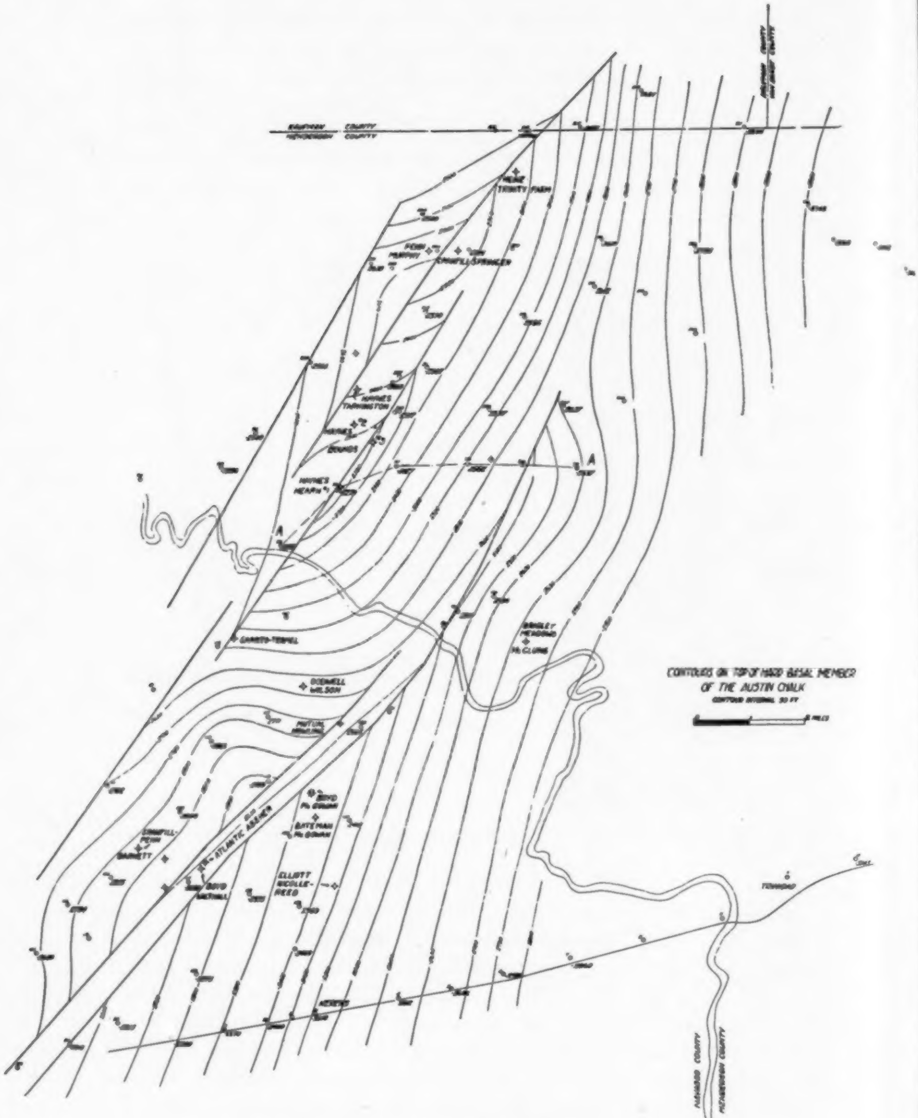


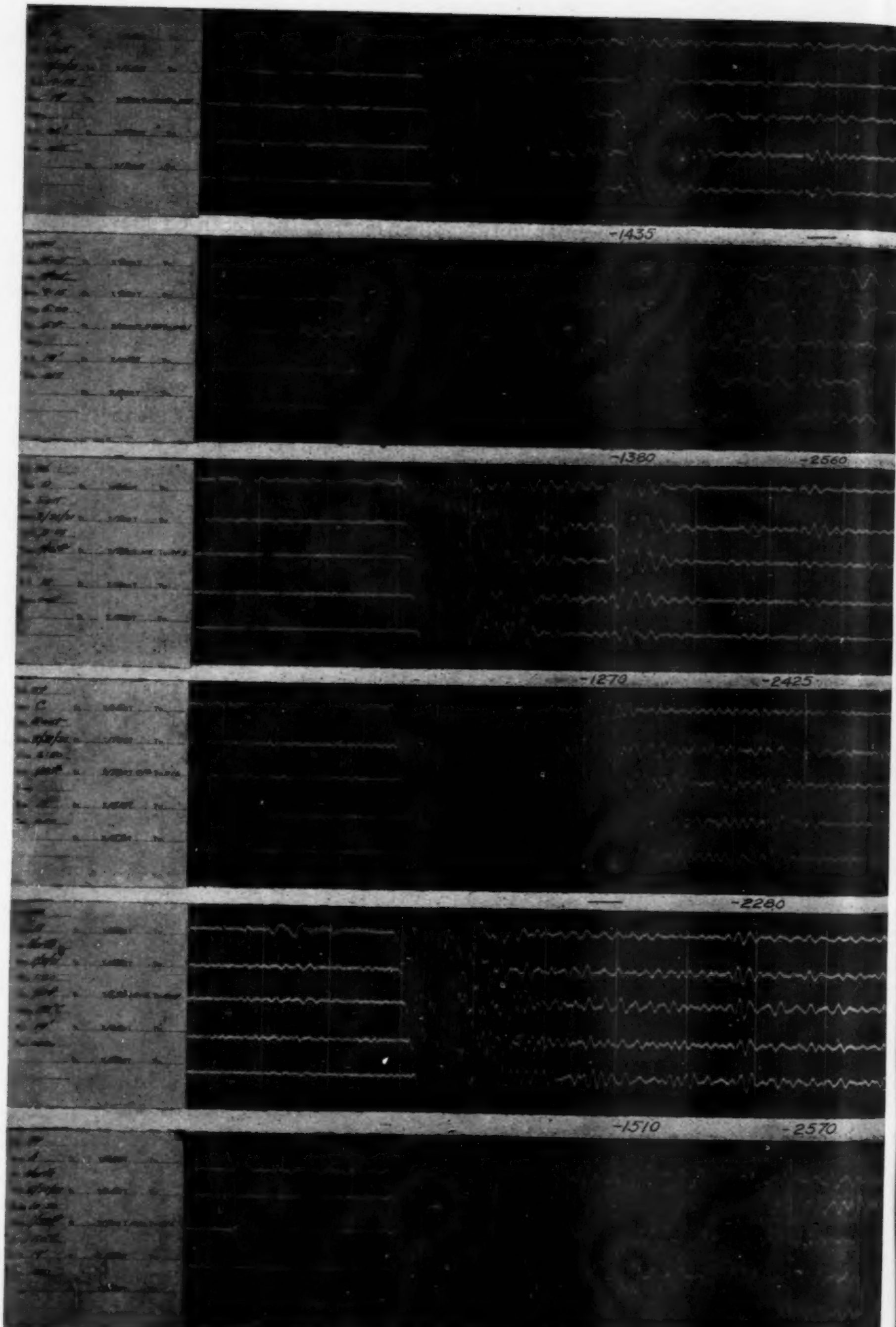

FIG. 3.—Reflection contours on top of basal member of Austin chalk.

tion, the absence of the reflection in this instance can hardly be called conclusive evidence of the presence of the fault.

Due to the absence of the Pecan Gap reflection, record F.P.58 is of special interest. As the amplitude of the Austin reflection on this record is larger than on any of the other records, the Pecan Gap reflection under normal conditions should be very large indeed. There can be little doubt that this must be the result of very abnormal subsurface conditions. It is seen from the cross section and contour maps that the normal reflection point for the Pecan Gap lies in the fault plane of the Pecan Gap. This fault, it should be noted, has been located by several other determinations. In many cases it is impossible to get any reflections very close to a fault, due probably to minor fracturing in the proximity of the fault plane. The presence of the Austin reflection in this case would indicate that the fault must be a fairly clean break without much minor fracturing.

## CONCLUSION

It is thought that the reflection seismograph may economically justify its use in many cases by permitting the location of a test well in the most advantageous position structurally and thus save the cost of many unnecessary wells.


-1435
-1380
-2560
-1270
-2425
-2280
-1510
-2570

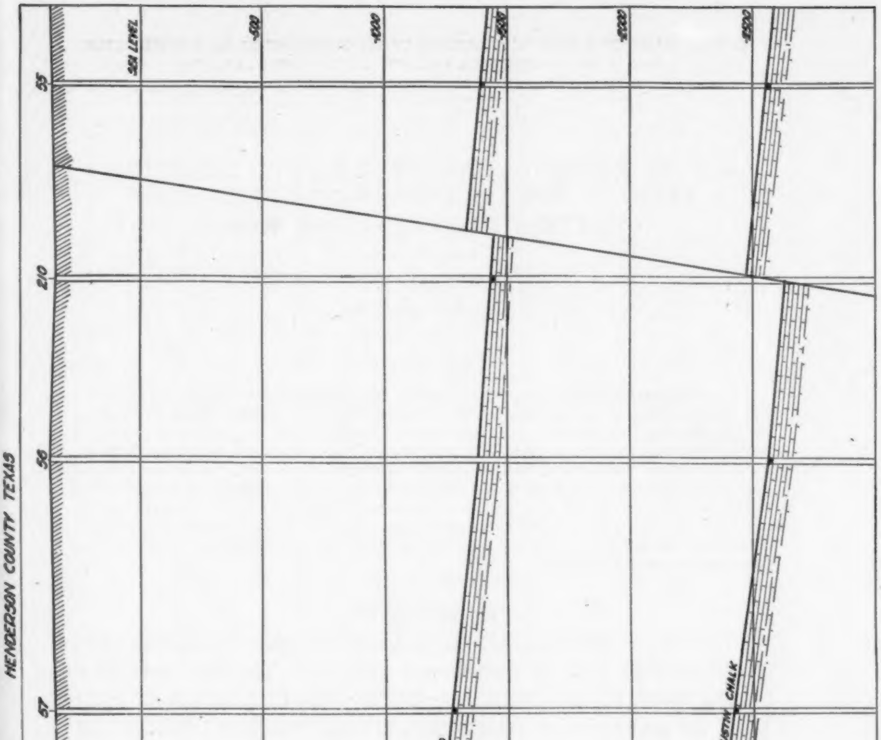



FIG. 4.—Cross section *AA* and corresponding reflection records. Horizontal length of section, 30,500 feet.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1212-1220, 2 FIGS., 4 PLATES

# USE OF RECORD CHARACTER IN INTERPRETING RESULTS AND ITS EFFECT ON DEPTH CALCULATION IN REFRACTION WORK[1]

T. L. ALLEN[2]
San Antonio, Texas

## ABSTRACT

In seismograph exploration, the author has encountered acoustic horizons which do not transmit seismic energy readily. The first impulse on the seismogram has a short period with small amplitude, and requires considerable energy to make it apparent at long distances. This horizon is underlain by one of slightly higher velocity which transmits the energy readily and has a distinctly different wave form. On account of the difficulty of energy transmission, the horizon which has the small "forerunner" wave might be interpreted as a lens and not a continuous horizon. By making use of the character of the wave form on the seismograms, the two horizons may be definitely identified, and the one which is a poor conductor of energy definitely proved to be a continuous acoustic horizon.

## INTRODUCTION

This paper covers a short discussion of a problem encountered in refraction work done in Venezuela during 1931. The work was done by the International Petroleum Engineering Corporation of New York, using electrical seismographs and radio equipment built by the Petty Geophysical Engineering Company of San Antonio, Texas. The writer was in charge of the party in the field.

The problem to be considered involved an interpretation of results in an area where an acoustic horizon transmitted the seismic energy poorly. Referring to profile *A*, Plate 1, it is evident that there are four acoustic horizons involved, with velocity values of approximately 2,000, 2,160, 2,580 and 6,510 meters/second, the first three being sedimentary, while the fast one represents the igneous basement. There were several other profiles shot in the same general area as profile *A* and all of them had the same general velocity values. Profiles *B*, *C*, and *D* were approximately 50 kilometers from profile *A*, and the sedimentary horizons had become thinner in this distance. Several profiles were shot in the distance between the two areas, and

[1] Published by permission of International Petroleum Engineering Corporation, 80 Maiden Lane, New York, N. Y. Read before the Association at the Oklahoma City meeting, March 24, 1932.

[2] Field manager, Petty Geophysical Engineering Company. Introduced by L. W. Blau.

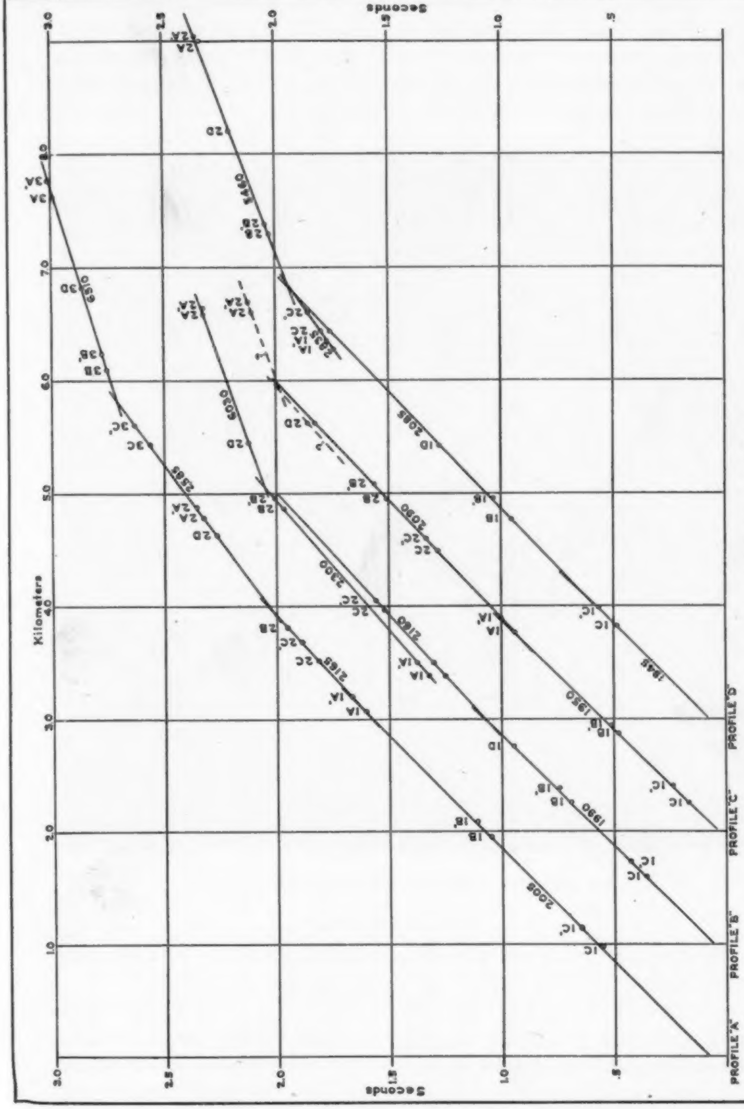



PLATE I - TIME-DISTANCE CURVES

PLATE I

their results showed a gradual thinning of the sedimentary beds and a gradual decrease in the velocity values. The seismograms shown in Plate 2 are the ones from which profile *B* is plotted, Plate 3 shows the seismograms from which profile *C* is plotted, and Plate 4 shows those from which profile *D* is plotted.

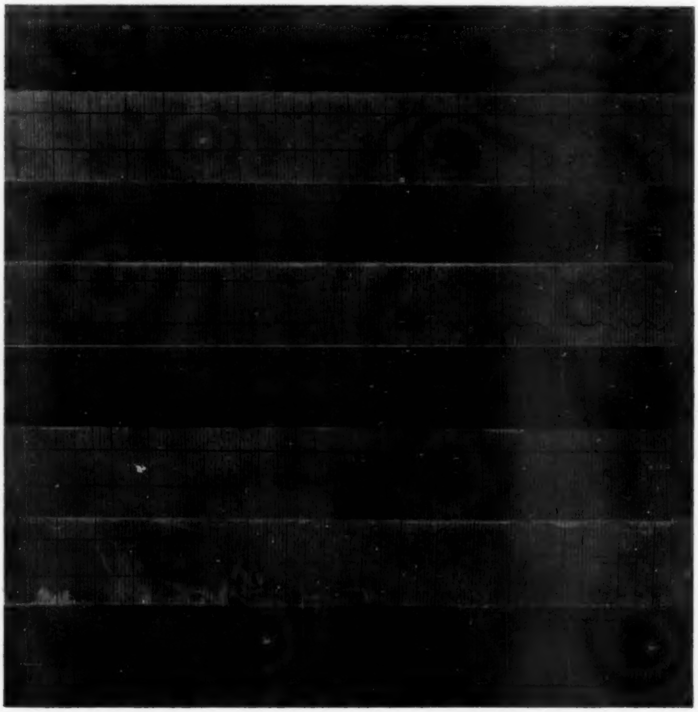


PLATE 2.—Seismograms for profile *B*.

STUDY OF RECORDS

A study of the three sets of seismograms reveals four distinct record characteristics. The first five seismograms of profile *B*, Plate 2, break sharply and plot on the surface velocity curve; the next four seismograms do not break sharply but have a small wave of short period for the first impulse followed by a wave with a sharp break and large amplitude. The small impulse and the sharp break were

both considered and are plotted on the profile. The sharp break with large amplitude is the first impulse on records 2*B* and 2*B′*, while on the longest three records the sharp break is preceded by an absorbed impulse which is characteristic of the igneous basement. Several other profiles in the same general area as profile *B* all had a small wave of short period on the second horizon which required large dynamite charges to bring out. A curve drawn through the points represented by the first small impulse or "forerunner" does not intersect the curve drawn through the points representing the sharp breaks of the third horizon until after the basement velocity curve intersects both of them. Should the small wave or "forerunner" be interpreted as a thin lens-like formation overlying the horizon which gives the sharp break, or is it a separate acoustic horizon? If the former, it might be disregarded as far as depth calculation is concerned, but if it is the latter its thickness must be considered.

### THEORETICAL CONSIDERATION

If the conditions shown in Figure 1 be assumed, it is possible to derive equations for the time-distance curves which these velocities

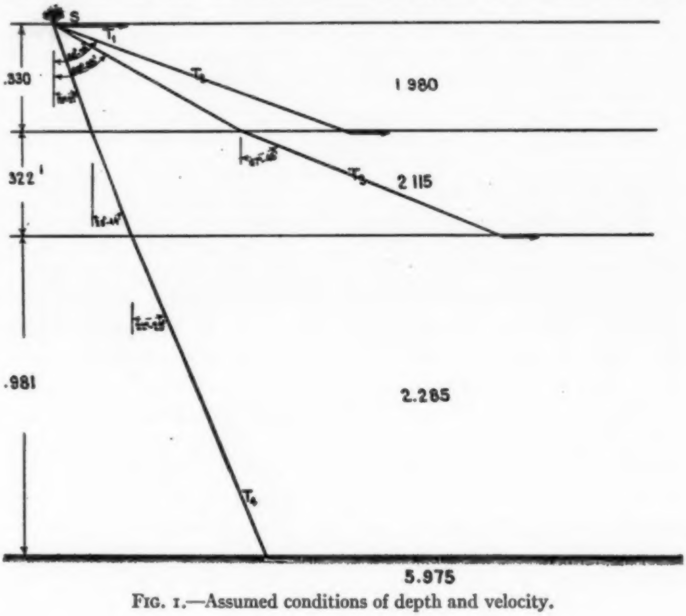



FIG. 1.—Assumed conditions of depth and velocity.

and thicknesses will give. The distance of the receiving station from the shot point will be designated as $x$, and the equations for the time through each path derived. For the surface layer, the general equation for the time is,

$$T_1 = \frac{x}{1.980}\cdot$$

The general equation for the time through the second horizon is,

$$T_2 = \frac{2 \times .330}{\cos 69^\circ 25' \times 1.980} + \frac{x - 2 \times .330 \times \tan 69^\circ 25'}{2.115}\cdot$$

For the third horizon, it is,

$$T_3 = \frac{2 \times .330}{\cos 60^\circ 03' \times 1.980} + \frac{2 \times .322}{\cos 67^\circ 46' \times 2.115} + \frac{x - 2 \times .330 \times \tan 60^\circ 03' - 2 \times .322 \times \tan 67^\circ 46'}{2.285}$$

and for the fourth horizon, it is,

$$T_4 = \frac{2 \times .330}{\cos 19^\circ 21' \times 1.980} + \frac{2 \times .322}{\cos 20^\circ 44' \times 2.115} + \frac{2 \times .981}{\cos 22^\circ 29' \times 2.285} + \frac{1}{5.975}[x - 2 \times .330 \times \tan 19^\circ 21' - 2 \times .322 \times \tan 20^\circ 44' - 2 \times .981 \times \tan 22^\circ 29'].$$

These are all straight line equations which may be reduced to the simple forms which follow:

$$T_1 = \frac{x}{1.980}$$

$$T_2 = .948 + \frac{x - 1.757}{2.115}$$

$$T_3 = 1.473 + \frac{x - 2.720}{2.285}$$

$$T_4 = 1.608 + \frac{x - 1.288}{5.975}\cdot$$

The curves represented by these equations are shown in Figure 2. It is apparent that the wave from the third horizon would never be the first impulse, since the intersection of the $T_2$ and $T_3$ curves is past the point where the $T_4$ wave arrives first. The only manner by which the third horizon velocity may be determined is to select the secondary waves on records shorter than 4.174 kilometers, which is the value of $x$ where the $T_2$ and $T_4$ curves intersect in this particular case.

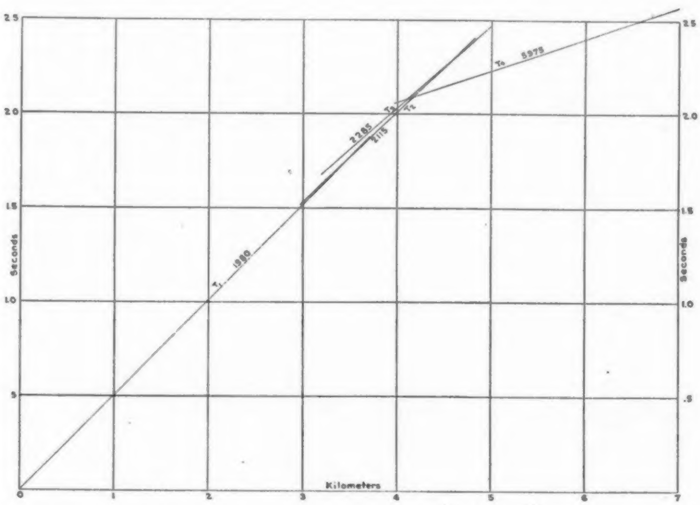



FIG. 2.—Time-distance curve for assumed conditions.

This theoretical consideration seems to indicate that the small wave or "forerunner" represents a distinct acoustic horizon and not a lens-like formation. If this be true, it should always give the first seismic impulse on the seismogram, provided there is enough energy available to bring it out. In Plate 3, there was more energy available on account of the shorter distances and the amplitude of the first impulse is quite large on all the seismograms except 2*D*. The period of the wave is quite short, however, indicating that it is the impulse characteristic of the second horizon. On Plate 4, records 1*A* and 1*A′* have a sharp break as the first apparent impulse, but a study of these seismograms under a glass shows a slight movement ahead of the apparent initial impulse. Record 2*C* was only about 100 meters longer

than 1*A′* but had four times as much dynamite, and the small forerunner wave is very evident on this record. This proves conclusively that the formation which transmits the small forerunner type of wave is a continuous acoustic horizon which does not transmit the seismic energy readily.

### CONSIDERATION OF DIFFERENT PHASES OF THE PROBLEM

The problem presented here might be thought of from two different angles. If all horizons had been of equal energy-carrying ability,

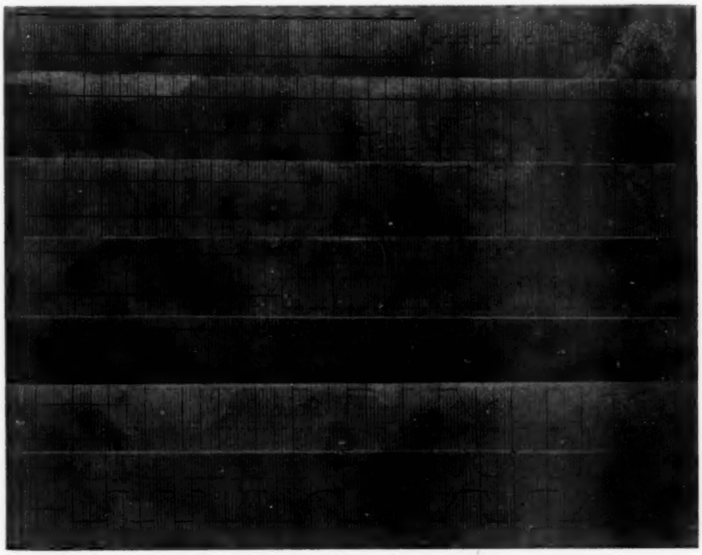


PLATE 3.—Siesmograms for profile *C*.

the third one would have been difficult to detect, due to the fact that the particular thicknesses and velocities are such that the third horizon impulse would never have been first. On the other hand, it would be easy to neglect the beds which transmitted energy poorly unless sufficient dynamite was used to make the first impulse large enough to be seen. In the area where this work was done, the dynamite charge was chosen that would give just enough amplitude to the second horizon wave to make it apparent, yet not so large that it obscured the large secondary impulse from the third horizon. In this manner,

it was possible to choose a primary wave and designate it as the second horizon impulse and also choose a secondary wave and consider it as a primary wave from the third horizon. If the second horizon had been omitted from the calculations, the total depth to the basement would have been too small and the surface horizon would appear much thicker. Omission of the third horizon from the calculation would also have made the total depth to the basement too small but would not have changed the thickness of the surface horizon.

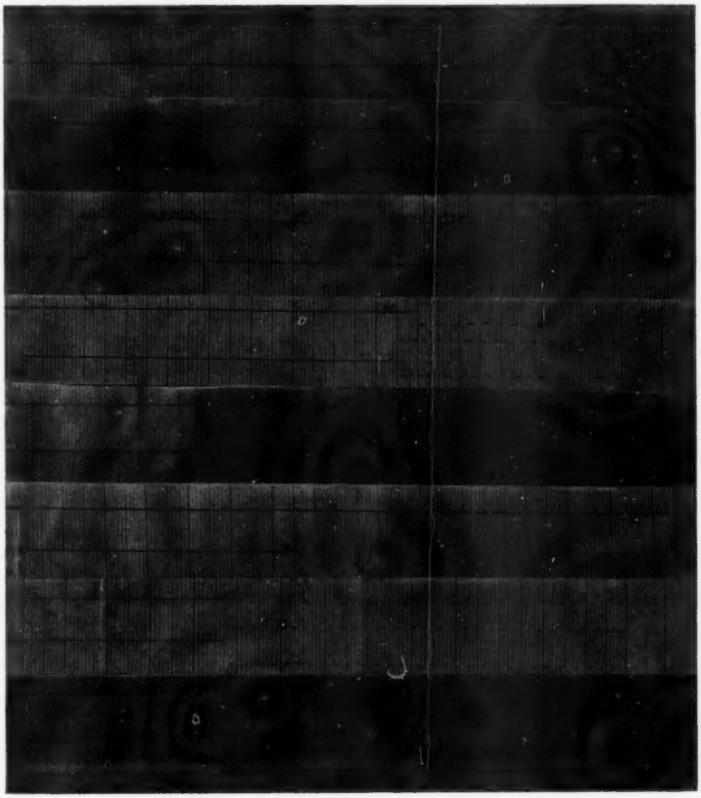


PLATE 4.—Seismograms for profile *D*.

### REASON FOR POOR ENERGY-CARRYING CHARACTER

The reason for poor energy transmission is probably due to alternating beds of hard and soft material, perhaps sandstones and clays. There is an area in the Gulf Coast where a poor energy-carrying horizon is found, and it is especially noticeable in Harris County, Texas. The movement on the seismogram is a small wave whose beginning is scarcely perceptible and is sometimes mistaken for a salt dome "forerunner." Recent work by the reflection method in the Gulf Coast region shows several reflections from the horizon which transmits the refracted wave poorly, indicating a change in density which would logically be explained by alternating beds. If the alternating beds which compose the acoustic horizon had slightly different velocity values, the refracted wave would gain a slight amount in the faster bed, and be gradually damped out.

### CONCLUSION

The seismic wave accurately shows the subsurface conditions. The character of the wave is affected by the various strata through which it passes, and a study of the wave character is important in the correct interpretation of seismic results. The possibilities of the seismograph as an accurate exploratory instrument have not been fully realized, and this paper is presented with the hope that further study along similar lines will broaden the scope of usefulness for this instrument.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1221-1229, 6 FIGS.

# SEISMOLOGICAL DISCOVERY AND PARTIAL DETAIL OF VERMILION BAY SALT DOME, LOUISIANA[1]

E. E. ROSAIRE[2] and O. C. LESTER, JR.[3]
Houston, Texas

ABSTRACT

The Vermilion Bay salt dome in Iberia Parish, Louisiana, was one of the first discovered by a geophysical survey of water-covered areas. The field organization and equipment of such a crew is described. The discovery and detail data are presented, along with the original interpretation of these data. The results of drilling are shown, and the agreement and disagreement of these tests with the original interpretations discussed to some extent.

## LOCATION

Vermilion Bay is one of the major features of the Louisiana coast line. The Vermilion Bay salt dome is located in the southeastern corner of the bay, but in the extreme southern portion of Iberia Parish, Louisiana. It is best reached by boat along the Boston Canal from Abbeville, or by car to Cypremort Point, and thence by boat to the dome.

## DISCOVERY

This salt dome was discovered on September 25, 1927, in a reconnaissance refraction exploration conducted for the Louisiana Land and Exploration Company by a Geophysical Research Corporation party[4] under the direction of the junior writer.

The discovery of this dome was of importance beyond the usual, for several reasons. Among these may be listed the following.

1. This salt dome was discovered as a result of the use of the seismograph in exploring large bodies of water. The Louisiana Land and Exploration Company was the first to launch a major exploration campaign with this definitely in view, using for this purpose two Geophysical Research Corporation parties,[5] equipped for water surveys.

[1] Read before the Association at the Oklahoma City meeting, March 25, 1932. Published by permission of the Louisiana Land and Exploration Company, and the Geophysical Research Corporation.

[2] Consulting geophysicist, 2210 Esperson Building.

[3] Geophysical Research Corporation.

[4] Within a month, this same crew had also discovered the Four Isle and Dog Lake salt domes, in southwest Terrebonne Parish.

[5] The other crew, under the direction of C. G. Rosaire, was the first to discover a salt dome during a water survey, since his discovery of the Calcasieu Lake salt dome antedated O. C. Lester's discovery of the Vermilion Bay dome by several days.

By virtue of their being first to embark upon this virgin field, these two refraction crews staged what is probably the most spectacular campaign in the history of geophysical exploration, discovering no less than eleven salt domes in 9 months. These successes, starting similar campaigns by other companies, caused the intensive exploration (by seismograph crews) of southeastern Louisiana, and further resulted in the discovery of six additional salt domes in this same area, all within a year after the discoveries of the Calcasieu Lake and Vermilion Bay salt domes.

2. This successful application of the seismograph to water explorations undoubtedly brings part, at least, of the Gulf of Mexico within the available petroleum reserves of this geological province, if or when the value of crude oil justifies the solution of such practical and legal complications as are apparent.

## OPERATIONS

Vermilion Bay varies in mean depth from 10 to 13 feet in an area of approximately 125,000 acres (Fig. 1). The operations in this instance, as in other water explorations of similar magnitude, were conducted entirely from boats. The crew was quartered in a houseboat with auxiliary barges for explosives and supplies, while the recording apparatus was mounted in fishing luggers 40 to 75 feet in length. A similar lugger was used in locating, planting, and firing the charges of explosives.

The explorations were conducted by the usual method of refraction fans. Communications and transmissions of time signals were effected by two-way radio operations on 180 meters, using 5-watt I C W transmitters. Distances from shot to recorders were determined from the air travel times of the explosive sound waves.

Though the analysis of such exploration data is comparatively simple, its acquisition involves the solution of many practical difficulties. Adverse winds may carry the sound wave above the recorders, or may lower the water level to such an extent that operations of any kind are impossible over the subsequent mud flats; and may even maroon the recording boats for as much as a week. In the latter case the resulting diet of canned tomatoes and oysters becomes rather monotonous after a few days. On the other hand, moderately rough water is no great handicap, since seasick observers have taken excellent records with the seismographs planted in water and mud at depths of 15–20 feet. Also, as this coast is not infrequently visited

by tropical hurricanes, the field crews watch the Coast Guard Weather Reports (received by radio) and occasionally have to run for land, returning later to salvage gasoline drums and boxes of dynamite scattered over the shore by sudden and severe squalls.

Even under such conditions, the explorations averaged 200,000 acres per month; and as much as 15,000 or more acres have been surveyed in a single operating day.

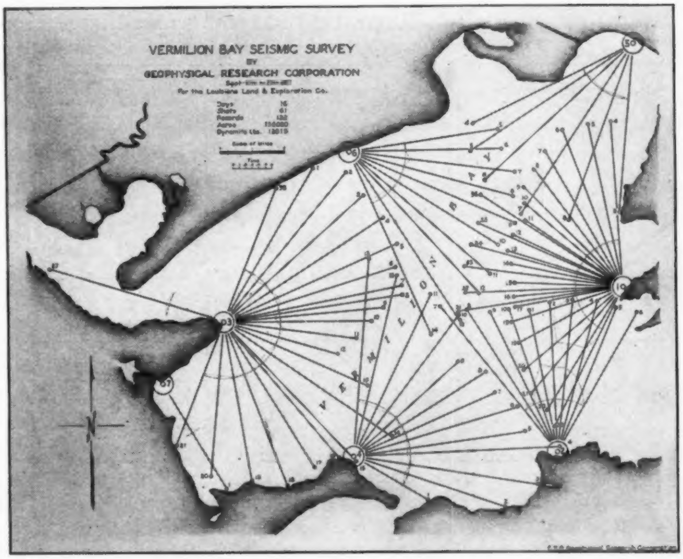



FIG. 1.—Refraction fan layout for exploration of Vermilion Bay.

In the survey of Vermilion Bay, three recording boats were used. Each was equipped with a radio transmitter and receiver, an oscillograph, and a velocity meter (geophone) recording through a vacuum tube amplifier. The timing device was an electrically operated 50-cycle tuning fork. The air wave was picked up by a carbon-button unit. The resulting records were developed immediately, thus guiding the observers in the size of the next shot. The instant of explosion was determined by the breaking of a wire wrapped around part of the charge of explosive, thus terminating the operation of the shot transmitter. In general, the charge of explosive was simply lowered to the

bottom of the water, or buried in a hole on shore. A smaller simultaneously detonated surface charge was used for the air wave distance determination. Travel times were read to hundredths of a second.

Distance determinations were made from the travel times for the air waves, corrections being used for wind velocities and directions, determined by compass and hand anemometers at the time of each shot. For short-shot lengths, up to about 5 miles, these were relatively accurate to about 200 feet. (At greater distances over land, large errors

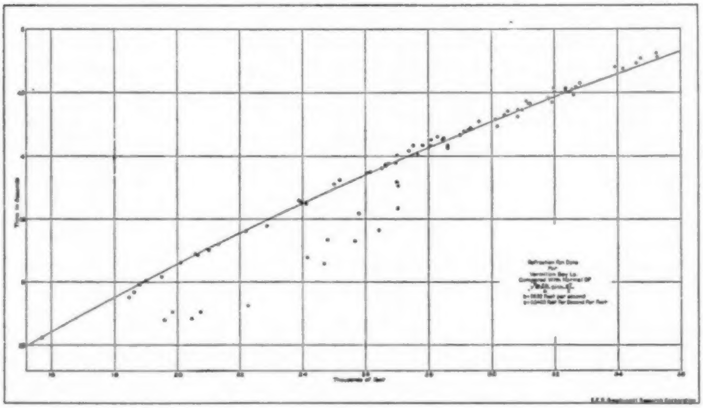


FIG. 2.—Travel time data for Vermilion Bay.

appeared in this method, as for instance, when an error of 2,000 feet appeared in a shot line 40,000 feet long.)

Distance determinations and final travel-time counts were made at headquarters in the houseboat. The travel-time data (Fig. 2) were plotted, and the normal relationship indicated by drawing the obvious "normal" travel-time curve. Travel times appreciably shorter than normal were then considered as suggesting the existence of a salt dome, and bona fide time differences checked by a cross fan.

### INTERPRETATIVE PROCEDURE

*Long distance refractions.*—The data collected in Vermilion Bay may be taken as typical of a shallow Gulf Coast salt dome. For convenience of study, the time intervals are plotted, on each line, from

an arc indicating normal arrival times. If minus time differences are plotted out from the shot point, an approximation is made to the outline of the wave front at the recording points. In the case of the Vermilion Bay data, the resulting pattern of time differences unmistakably indicated the presence of a previously unknown salt dome.

The smooth curve used as the "normal" in Figure 1 is calculated from the travel-time relationship

$$X = \frac{2b}{a} \sin h \frac{aT}{2}$$

for a linear increase of velocity with depth. The constants $b$ (surface velocity) and $a$ (increase in velocity per foot of depth) were determined by trial, and found to be

$$b = 5{,}633 \text{ feet per second}$$

$$a = 0.5483 \text{ foot per second.}$$

The penetration, $Z$, for such a curve is

$$Z = \sqrt{\frac{x^2}{4} + \frac{b^2}{a^2}} - \frac{b}{a}.$$

*Short refraction data.*—A short negative profile was shot north from *SP* 1, to serve as a "normal" in mapping the top of the dome. This is shown in Figure 3.

An interesting feature of this profile is that the extrapolated travel-time curve indicates a negative time for zero distances. This is to be expected for explosion-generated data, and indicates the abnormally high velocity of sound in the immediate neighborhood of the explosion. However, in comparison with the greater number of such short refraction profiles, these data are exceptional, since the usual data indicate a plus time at zero distance, due to the general existence of a low-speed layer at the surface of the ground (weathered or aerated zone). In the case of the Vermilion Bay data, there is apparently no aerated zone,[1] so that there is opportunity to observe the effect of the abnormally high sound velocities in the immediate vicinity of the explosion.[2]

[1] This is not necessarily an obvious conclusion, since in some cases of water-covered marsh, definite geophysical evidence of an aerated zone has been found on the shorter travel-time curves. As Paul Weaver has pointed out in "Geophysics of the Soil," this is to be expected in the case of thick layers of soil being formed from rotting vegetation.

[2] A. B. Wood, *Textbook on Sound*, p. 266.

This short profile can also be fitted by a travel-time curve such as that approximated by the longer refraction data. For the shorter data, the constants are

$$b = 4{,}990 \text{ feet per second}$$
$$a = 1.25 \text{ feet per second per foot.}$$

The difference in the values of these "constants" for the two sets of data is significant, since it is an indication of the extent to which

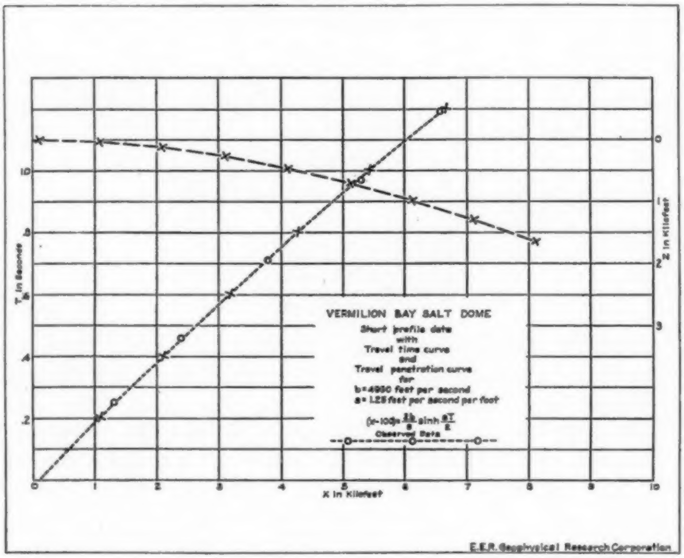



FIG. 3.—Short refraction data for Vermilion Bay.

these data can be approximated by a linear increase of velocity with depth.

*Partial refraction detail.*—The location of the dome by refraction fans was recognized as too qualitative for drilling. Therefore, with the thought of securing more definite information as to the depth and location of the top and flanks, the following detail survey was carried out.

Figure 4 shows the location of these refraction profiles, together with the resulting interpretation of the outline. The profile data are

shown in Figure 5 and Figure 6. The solid part of the travel-time curves are taken from the negative profile data described in Figure 3.

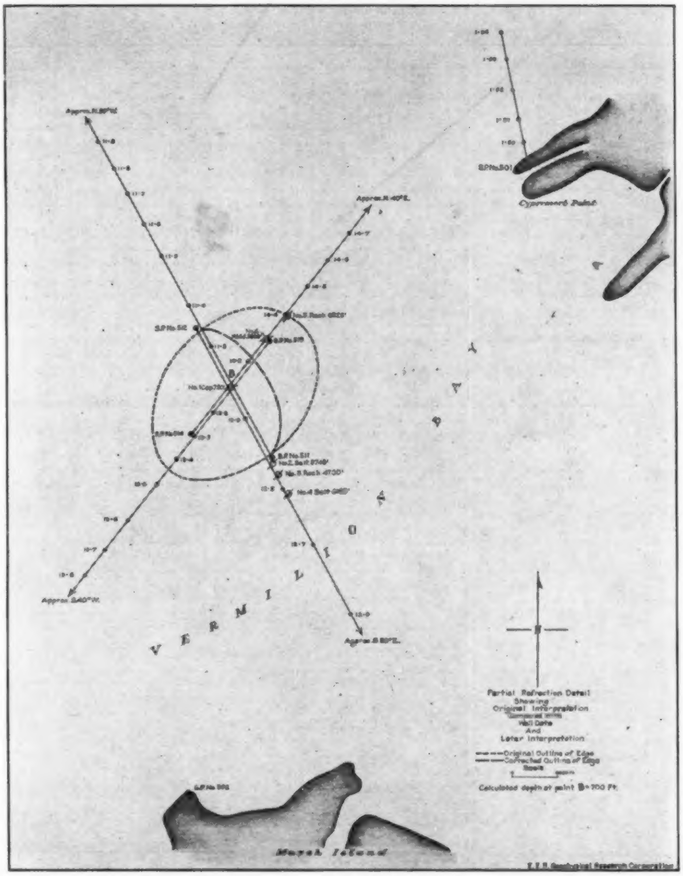



FIG. 4.—Refraction profile layout for partial detail of Vermilion Bay salt dome.

All four of these profiles show the usual features of a refraction profile characteristic of a shallow salt dome. The most essential feature is the more or less sudden decrease in apparent velocity shortly after

the recording points pass well beyond the salt flank. The junior writer, at the time of this detail, made a depth calculation of 800 feet to cap or salt, at the intersection of the profiles. The agreement with the results of the well later drilled at this point was very satisfactory.

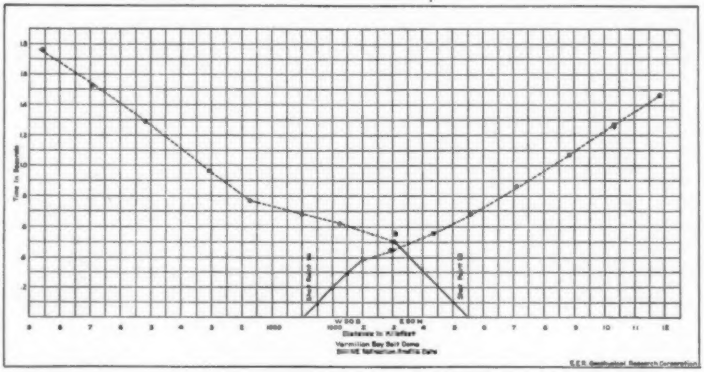


FIG. 5.—Southwest-northeast refraction profile data, Vermilion Bay salt dome.

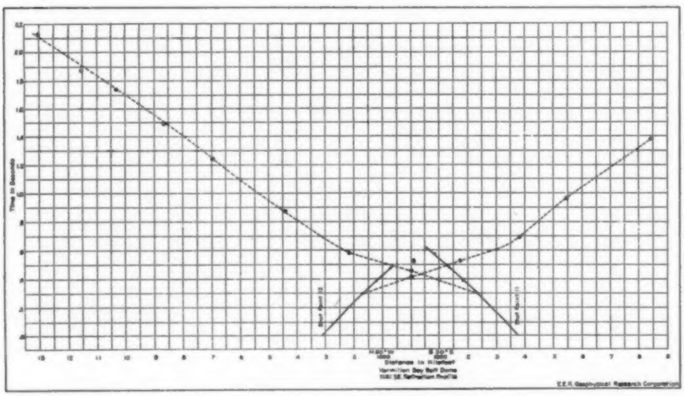


FIG. 6.—Northwest-southeast profile data, Vermilion Bay salt dome.

The original interpretation of the outline of the dome (dotted) was made in the New York office, not in the field. The southeast flank location was good, as shown by the findings in the wells drilled on the line. The only other check of this outline was made on the northeast

flank, with disappointing results. Well No. 5, supposedly a location similar to Well No. 2, was abandoned in rock at 6,500 feet. Well No. 6, well inside this estimated edge, was abandoned at 5,824 feet without finding dome materials, when cap or salt was expected not deeper than 900 feet. A recent revision of the interpretation on this flank was made by the junior writer, and led to the location of this edge as shown by the dashed line. As no further wells have been drilled since No. 6, the original interpretation of the northwest and southwest flanks, and the re-interpretation of the northeast flank remain unchecked to date.

With the experience accumulated, since this detail, on several other domes, the writers are in a position to comment on the job. It is obviously incomplete, since four points, no matter how well determined, can hardly furnish satisfactory control on the periphery of a salt dome like that in Vermilion Bay. Later practice was to locate eight points, reversing all profiles. These additional points, determined on stronger evidence, resulted, in the case of the Lake Barre salt dome, in commercial production by the first flank test, followed by a string of nine successive flank producers around the periphery of the dome.

In addition, the profile data on the northeast flank somewhat definitely indicate that this flank slopes less steeply than any of the other three. Failure to realize the amount of this slope (as shown by the apparent velocities) undoubtedly played a major part in the erroneous location of this flank.

Finally, these conclusions were reached on profile data with too low a survey density. Recorder intervals of 1,500 feet can hardly be expected to locate salt dome flanks to plus or minus 250 feet. In the later details, these recorder intervals were cut down to as little as 250 feet, along the profile.

In presenting the data for publication, attention is called to the fact that curved lines have been used to approximate the travel-time curves. At the time of this survey, field practice was to use successive, intersecting straight lines, but for the past 3 years, curved path interpretations have entirely replaced the older, empirical, strong-arm methods of attack in almost all phases of refraction surveys. In view of this, the writers feel justified in restricting their case treatment to the earlier predictions, and so indicating, to one experienced in the art, the contrast between the old and the new interpretation methods.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1230-1234, 2 FIGS.

# SEISMIC WEATHERED OR AERATED SURFACE LAYER[1]

O. C. LESTER, JR.[2]
Tulsa, Oklahoma

## ABSTRACT

The existence of a comparatively thin surface layer with a low velocity characteristic has been recognized in seismic work for several years, and has been generally referred to as the "weathered layer." This low velocity surface characteristic has been found to be almost universally present regardless of the nature of the surface deposits, and does not conform to the geologic weathering of the area.

The purpose of the writer is to offer as an explanation of this phenomenon, the mixture of air in a free state with surface materials. Theoretical calculations, if the earth is assumed to be a fluid, indicate that velocities less than that of sound in air should be obtained from such mixtures. This is borne out by experimental data, as far as available, indicating that this so-called weathered layer might properly be termed an "aerated" layer.

It must be said at the outset that the conclusions of this paper are based on meager field data. The primary argument arises from theoretical study and postulates certain effects. These effects, however, have been confirmed by experiment in so far as such experimental data are available. The purpose of the discussion is, first, to present a probable explanation of a phenomenon which has been recognized and dealt with—though unexplained; and second, as a result of such explanation, to suggest a more descriptive and less confusing name than that of "weathered."

The existence of a comparatively thin surface layer with a low velocity characteristic has been recognized in seismic work for several years, and it has been generally referred to as the "weathered layer." This condition has been found to be almost universally present, regardless of the nature of the surface deposits, and has been recognized from its low velocity characteristic rather than by any physical or geological difference between it and the materials immediately below. The drilling of deeper shot holes, below the depth of this low velocity horizon, has failed to indicate any visible differentiation between it and adjacent materials.

[1] Read before the Association at the Oklahoma City meeting, March 25, 1932.

[2] Geophysical Research Corporation, Box 2040.

Since the recognition of this stratum, various methods have been applied to correct for the abnormally slow travel time through it (particularly in reflection work), but little or no attempt has been made to explain its nature, or to determine the cause of its important characteristic.

Data taken in various places, over a wide area, from Kansas and Oklahoma to the gulf coasts of Mississippi, Louisiana, and Texas, have indicated that this layer *may* vary in thickness from practically zero to more than 150 feet, though the general average is approximately 50 feet. The velocity of sound in this "weathered" material, though variable, is always comparatively low and a general average might be placed between 2,000 and 2,500 feet per second; while the average velocity of sound in the same materials immediately below is found to be generally about 5,600 feet per second.

As this top layer is at the surface of the ground and exposed, as its low velocity characteristic exists almost universally regardless of composition, and as this low velocity characteristic could result from a broken, disintegrated or loosely bedded condition, the term "weathered layer" is perhaps natural. This term has been in use for some time for the sake of convenience and for lack of a better one, though it has been granted that this layer does not, in many cases, conform to the geologic term "weathered." In the Gulf Coast region, for example, the geophysical weathered layer is exceptionally uniform and thin, though the geologic term "weathered" could be applied to the sediments at considerable depths.

The suggestion that the "weathered layer" might be associated with the regional ground-water table has often been made, but though in some areas the thickness of this material seems to be determined by the depth of the water table, this has not been found to be true in a sufficient number of cases to permit a general conclusion.

The extremely low velocities (approaching, or even less than, the velocity of sound in air) that have been obtained in some areas, led to the idea of air inclusion in the surface materials as the cause.[1]

With this idea in mind it was predicted that short (shallow) refraction profiles would show lower and lower velocities with shallower depth penetrations, approaching if not actually equaling the velocity

[1] The discussion here refers to air mixture in a free state—not in solution. As $V=\sqrt{\frac{E}{P}}$ air or gases may be considered together, as opposed to fluids or solids, because of the order of magnitude of difference in $E$ and $P$ for these two classes of materials. $E$=elasticity: $P$=density.

of sound in air, as the air became present in larger and larger proportions near the surface. The few profiles in which velocities lower than that of sound in air had been indicated, were considered interesting but somewhat anomalous, and were strongly suspected of containing some unseen error. A discussion of sound velocities in air-water mixtures,[1] which was pointed out by E. E. Rosaire, was the direct cause of the experiment here discussed. This experiment was carried out in the Gulf Coast region near Houston, Texas.

On the assumption that Gulf Coast gumbos may be treated as fluids, within limits, calculation of theoretical velocities to be obtained from earth-air mixtures in varying proportions were carried out from the equations given in the article mentioned,[2] namely:

$$V = \sqrt{\frac{E}{P}} = \sqrt{\frac{E_1E_2}{\{XE_2 + (1 - X)E_1\}\{XP_1 + (1 - X)P_2\}}}\,.$$

Where:

$P_1$ = density of air = .0012
$E_1$ = elasticity of air = $1.2 \times 10^6$
$P_2$ = density of earth, assumed as 1.9
$E_2$ = elasticity of earth, computed as $5.58 \times 10^{10}$
$X$ = proportion air to total by volume
$1 - X$ = proportion earth to total by volume
$V$ = velocity of sound in mixture

If the values of the composite velocities be plotted against proportions of air to earth, a curve of the form in Figure 1 is obtained.

Though this curve should perhaps be considered only qualitatively because of the assumption of earth as a fluid, it indicates the probability of obtaining velocities from earth-air mixtures, whose magnitudes may be actually less than that of sound in air alone. This prediction has been verified experimentally by shooting a short detailed refraction profile, extreme precautions being taken to muffle the shot point and hence eliminate any effect of the air wave. The recording was begun at a distance of 5 feet from the shot point and carried out on the surface to a distance which definitely indicated the "unweathered" velocity on the time-distance curve. This curve is shown as curve ($A$) in Figure 2.

[1] A. B. Wood, *A Textbook on Sound*, pp. 327–28.

[2] A. B. Wood, *op. cit.*

As can be seen from the curve, a velocity within the weathered layer is indicated (slope of curve near origin) as low as 550 feet per second, while the velocity of sound in air alone is approximately 1,100 feet per second. Assuming the low velocity to be due to the inclusion of air as postulated, we would naturally expect the velocity to be

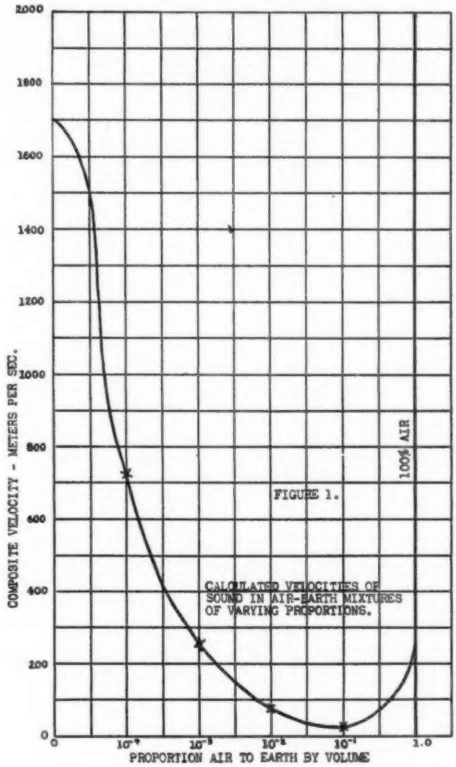



FIG. 1

lowest nearest the surface, where the proportion of air should be greatest. Referring this velocity (550 feet per second) to the curve (Fig. 1), the corresponding air concentration is 0.001 part by volume, which seems probable in the near-surface materials. A computation of the depth corresponding with the "break-point" of the time-distance curve indicates 7½ feet as the thickness of the "aerated layer."

After completion of this profile, a hole was dug at the shot point and the top of the water table was determined to be at a depth of slightly less than 8 feet. On the assumption that below the water table all air in a free state is displaced by water, whose density and elasticity are of the same order of magnitude as the earth under consideration, and hence has no material effect on the velocity of transmission of sound through such substance, both the shot point and recorders were lowered to the top of the water table. At this depth the shorter or "weathered" portion of the profile was re-shot with the result shown in curve (*B*), Figure 2.

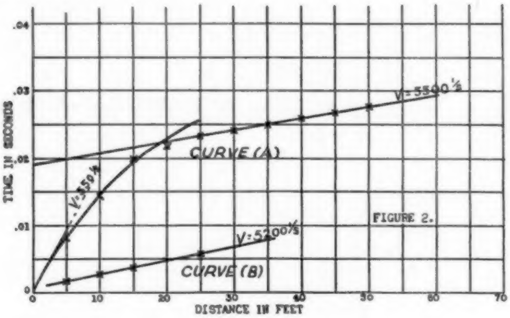



FIG. 2

On examination, this curve indicates an "unweathered" velocity (5,200 feet per second), which passes through the origin with only that curvature which is to be expected with a slight increase of velocity with depth. At the same recording distances from the shot point, the "weathered" portion of the time-distance curve has been eliminated with the elimination of the "aerated layer." The obvious conclusion is that where the water table is sufficiently shallow the thickness of the aerated layer is determined by its position. However, if the water table be at considerable depth, the "weathered" thickness is determined by the depth to which any appreciable amount of air penetrates.

This explains, in a measure, the sometimes extreme variation of "weathered" thickness with different surface materials. It would also predict a change of weathered thickness with wet and dry seasons.

Though these experiments have not been carried out to such an extent as to make the conclusions indisputable, it may be said that all the experimental data obtained favor the theoretical predictions resulting from the assumption of an "aerated" layer.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1235-1249

# ACCURACY OF DETERMINATION OF RELATIVE GRAVITY BY TORSION BALANCE[1]

DONALD C. BARTON[2]
Houston, Texas

## ABSTRACT

Determination of relative gravity by the Eötvös torsion balance has been shown by Oltay and others to be as accurate as the determination by the invariable pendulum. In the present paper, the probable error of the torsion balance determination of relative gravity is calculated from the error of closure of 45 traverses comprising 2,800 stations, most of them in the Gulf Coast region. The probable error of each individual observation in those surveys is calculated to have been $\pm 2.2$ Eötvös units for the traverses taken together, or from $\pm 1.9$ $E$ for the traverses with the larger station interval to $\pm 5$ $E$ for the traverses for the small station interval. But the greater error of the individual observations in the traverses which have the shorter station interval has been compensated, intentionally, by that shorter interval, and the probable error of the determination of relative gravity by those 45 traverses is approximately 0.4 milledyne per 10 kilometers of traverse without regard to the magnitude of the probable error of the individual observations or of the station interval. The probable error of the determination of relative gravity between key points in good torsion balance surveys presumably is approximately $\pm 2.5$ to $\pm 3.5$ $E$ per 10 kilometers airline distance between the two places. If pendulum determinations of relative gravity are used to supplement and to increase the accuracy of torsion balance surveys, there is a minimum interval at which the pendulum stations should be placed, for at lesser intervals the determination of relative gravity by the torsion balance is more accurate than that by the pendulum. That minimum interval ranges from 100 to 200 kilometers for the pendulum observations of the first quarter of the century to 8 to 50 kilometers for first class modern pendulum observations.

The relative accuracy of the determination of relative gravity by good torsion balance surveys in favorable terrane has been shown by Oltay, Jung, Numerov, and others to be comparable with the accuracy of the determination of relative gravity by the invariable pendulum during the past quarter century. The differences between the relative gravity by the torsion balance and pendulum on six traverses in the Arad district of the Hungarian plain were respectively 0.001, 0.001, 0.004, 0.000, 0.005, 0.000 cm. sec.$^{-2}$ The respective lengths of the traverses were 12, 9, 13, 20, 42, and 50 kilometers.[3] The probable error of the pendulum observations was calculated to

[1] Read before the Association at the Oklahoma City meeting, March 25, 1932.

[2] Consulting geologist and geophysicist, Petroleum Building.

[3] Karl Oltay, "Die Genauigkeit der mit der Eötvösschen Drehwage Durchgefuhrten Relativen Schwerkrafts-messungen," *Geodätische Arbeiten d. Baron R. v. Eötvösschen Geophysischen Forschungen*, No. III (Budapest, 1928).

be ±0.001 cm. sec.$^{-2}$ In the surveys in the Ries area of Bavaria, the differences between the determination of relative gravity by the torsion balance and the pendulum for six different lines were 0.003, 0.000, 0.000, 0.002, 0.003, 0.001 cm. sec.$^{-2}$ The lines ranged from 4 to 6 kilometers in length.[1] In the Ural Emba district of Russia, the differences were 0.001, 0.002, 0.007, 0.004, 0.003, cm. sec.$^{-2}$ The length of the traverses ranged from 9.5 to 15 kilometers.[2] In the Grosny district of Russia, the differences were 0.001, 0.002, cm. sec.$^{-2}$ and the lengths of the traverses ranged from 9.5 to 19 kilometers. As the probable error of the pendulum observations was ±0.001 to ±0.002, and as errors of three times the probable error should be expected to be fairly common, the torsion balance surveys gave as accurate a determination of relative gravity as did the pendulum observations. But from the data, it is impossible to tell whether the determinations of relative gravity by those torsion balance surveys were more accurate than those by the pendulum.

The accuracy of the torsion balance determinations of the gradient has been checked by the writer by calculation of the normal northward (planetary) gradient from torsion balance observations and comparison of that value with the theoretical value. The theoretical value was 7.14 *E* north in comparison with the value of 7.4 *E.*, N. ¾°E., which was calculated from the torsion balance observations.[3]

The present paper reports the determination of the effective accuracy of the (horizontal) gradient which is observed with the Eötvös torsion balance and of the accuracy of relative gravity which is calculated from the gradient.

The data on which the study is based consist of the error of closure in relative gravity in forty-five closed traverses from commercial torsion balance surveys. The length of the traverses ranged from 3 to 144 kilometers and in twenty-eight of the traverses, the lengths were evenly distributed over the range of 10 to 40 kilometers. The interval between stations on thirty-two of the traverses was 300–500 meters, on five traverses, 150± meters, and on eight traverses, 600–800 meters. The instruments which were used on the surveys mainly

[1] Karl Jung, "Drehwagemessungen im Ries bei Nordlingen," *Zeitschrift für Geophysik*, Vol. 7 (1931), pp. 18–19.

[2] B. Numerov, "Results of the General Gravity Survey in the Emba District," *Zeitschrift für Geophysik*, Vol. 5 (1929), pp. 268–70; and "Results of Gravitational Observations in the Region of Grosny in 1928," *ibid.*, Vol. 5 (1929), pp. 271–75.

[3] Donald C. Barton, "Gravity Measurements with the Eötvös Torsion Balance," in "Physics of the Earth," Vol. II, "The Figure of the Earth," *Bull. National Research Council*, No. 78 (February, 1931), pp. 186–87.

were the small type of the Süss "Original Eötvös" torsion balances and, on a few traverses, large Askania (automatic) instruments. The calculation of relative gravity around each traverse was made by a method in which superposition of a transparent graph over a gradient arrow gives the spacing of the isogams at that station; the isogams are sketched forward toward the next station and are bent as the experience of the geophysicist and the exigencies of the adjacent gradient arrows seem to demand. Single abnormal gradient arrows were neglected or given reduced weight according to subjective estimation of their value. The location of most of the surveys was in the Texas-Louisiana Gulf Coast within 150 miles of the coast, but a few of the surveys were farther inland and some of the surveys were located outside of Texas and Louisiana. Most of the terrane was good, but a few of the surveys were made in areas in which caliche was present in the subsoil and other surveys were made in river bottoms. The magnitude of the gradient most commonly was less than 20 $E$. The station sites on a few of the surveys were prepared with the meticulous care of the European custom, but on most of the surveys, slightly less care was used. Probably two-thirds of the observations were made during the day-time and one-third at night. The general rate of occupation of stations was two stations per day per instrument and two stations per night per instrument if observations were taken at night, although in about a quarter of the surveys, the rate of observation was one station during the day and two at night per instrument. These surveys were made in commercial oil prospecting in which, generally, speed and moderate accuracy are regarded as more important than high scientific accuracy, and the purpose of the surveys was qualitative or only roughly quantitative rather than accurately quantitative. The surveys were made by many different torsion balance parties. Most of the observers were not highly trained scientists.

The precision of scientific measurements of such quantities as gravity in America is stated in terms of what is called the "probable error"; in Continental Europe, the "mean square error" is used; the "probable error" is 0.6745 times the "mean square error." The term "probable error" is a technical term and is defined as the value such that half of the errors which are likely to occur in a large number of measurements of the quantity will be larger and half smaller; that is, if the determination of gravity at a station is stated in an American publication to be $978.569 \pm 0.001$ cm. sec.$^{-2}$, it is understood that there

are 50 chances out of 100 that algebraically, the actual error is less than $-0.001$ or greater than $+0.001$ and that there are 50 chances out of 100 that algebraically, the actual error will be between $-0.001$ and $+0.001$. According to the theory of the "probable error," the actual error will be five times the "probable error" 1 time in 1,000, four times the "probable error" 7 times in 1,000, three times the "probable error" 43 times in 1,000, twice the "probable error" 177 times in 1,000. The "probable error," therefore, affords a method of comparing the precision of different measurements and of determining the probable range within which the actual error of a measurement of quantity may lie.

The "probable error"[1] of a series of measurements depends upon the "probable error" of each measurement, the number of measurements, and the character of the series of measurements. If $PE$ is the "probable error" of the series, if $pe-1$, $pe-2 \cdots pe-n$ are the respective "probable errors" of $n$ measurements numbered, 1, 2, $\cdots$ to $n$ and if the series consists of repeated measurements of a single quantity, the "probable error" of the arithmetic mean of the measurements is:

$$PE = \frac{pe}{\sqrt{m}} \tag{1}$$

if the $pe$'s are all the same. But if the series consists of a series of consecutive applications of the measuring device, as for example, the consecutive use of a surveyor's tape, in measuring the length of a line which is longer than the tape:

$$PE = \sqrt{(pe_1)^2 + (pe_2)^2 + \cdots (pe_n)^2} \tag{2}$$

or if the $pe$'s are all the same:

$$PE = \sqrt{n}\, pe \tag{3}$$

The "probable error" ($pe$) of a mean in terms of the actual error ($ae$) of each measurement is given by the formula:

$$PE = 0.6745\sqrt{\frac{(ae_1)^2 + (ae_2)^2 + \cdots + (ae_n)^2}{n}}\,. \tag{4}$$

The accuracy of torsion balance surveys can be expressed by a probable error which can be calculated by the formula:

[1] Mansfield Merriman, *A Textbook on the Method of Least Squares*, 8th ed. (1911), pp. 66–79.

$$(5)\ PE_{U_{xz}} = 0.6745\sqrt{\frac{\left(\frac{EC_1}{L_1}\right)^2 N_1 + \left(\frac{EC_2}{L_2}\right)^2 N_2 + \cdots \left(\frac{EC_n}{L_n}\right)^2 N_n}{n}}$$

where:

$EC_1$, $EC_2$, $\cdots$ $EC_n$ are the respective errors of closure in $\Delta g$ of $n$ closed torsion balance traverses numbered from 1, 2, $\cdots$ to $n$;

$N_1$, $N_2$, $\cdots$ $N_n$ are the respective number of stations in those traverses;

$L_1$, $L_2$, $\cdots$ $L_n$ are the respective lengths of those traverses in centimeters;

$n$ is the number of traverses; and

$PE_{U_{xz}}$ is the probable error in the dimensions of the gradient.

The formula is adapted from Merriman's formula:[1]

$$(6)\qquad PE = 0.6745\sqrt{\frac{1}{n}\left(\frac{d_1^2}{L_1} + \frac{d_2^2}{L_2} + \cdots + \frac{d_n^2}{L_n}\right)}$$

where $PE$ is the probable error of each measurement with a surveyor's chain. It is assumed that the length of ($n$) lines (1, 2, $\cdots$ $n$) has been measured with the chain and is expressed in chain lengths; and that two measurements of each line were made. The respective differences between those duplicate measurements of each line are represented by $d_1$, $d_2$, $\cdots$ $d_n$ and the length of the respective lines in chain lengths by $L_1$, $L_2$, $\cdots$ $L_n$. $PE$, then, is the probable error of any one of the many single measurements of the chain. The probable error of the measurement of each line, then, can be calculated by formula (3) from the $PE$ which has been obtained by formula (6), and from the number of individual consecutive measurements with the chain which were necessary to measure the length of the line.

The measurement of $\Delta g$ by the torsion balance around a series of closed traverses is comparable to that duplicate measurement of each of a series of lines with a surveyor's chain. Each duplicate measurement of the length of the line may be regarded as a closed traverse which will consist of as many single measurements with the chain as the length of the line in chain lengths. A torsion balance traverse which is composed of $N$ successive stations may be regarded as $N$ consecutive measurements of a line comparable with those consecutive applications of the surveyor's chain to obtain the length of those lines. The error of closure of $\Delta g$, ($EC$), of a closed torsion balance

[1] *Op. cit.*, p. 103.

traverse is comparable with the difference, ($d$), between the duplicate measurements of the length of a line with the surveyor's chain; and the number of torsion balance stations, $N$, is comparable with the number of applications of the surveyor's chain.

The formula (6), therefore, may be re-written in the notation which we have assumed for the torsion balance surveys, to read:

$$PE = 0.6745\sqrt{\frac{1}{n}\left(\frac{\overline{EC}_1^2}{N_1} + \frac{\overline{EC}_2^2}{N_2} + \cdots \frac{\overline{EC}_n^2}{N_n}\right)} \tag{7}$$

The error of closure, $EC$, is in terms of $\Delta g$ (that is, cm. sec.$^{-2}$) and the probable error ($PE$), therefore, would be given in terms of $\Delta g$ per unit of measurement which according to our preceding assumptions is the station interval. The latter rather commonly is fairly constant within a traverse, but is variable from traverse to traverse. The calculation of $\Delta g$ over a station interval has the mathematical form of a gradient times distance, that is, times the length of the station interval; and, therefore, any error in $\Delta g$ over a station interval will tend to be lineally proportional to the length of the station interval. The calculated "probable error" in terms of $\Delta g$ and of the inconstant station interval would be useless. The "probable error," however, may be reduced to the dimensions of a gradient and then will be independent of the length of the station interval. All error in the calculation of $\Delta g$ over a station interval may be assumed to be in the gradient, if, as we usually assume, the stations are close enough together so that the variation of the gradient is linear from station to station. The probable error in $\Delta g$ over a station interval, then, will vary linearly with the length of a station interval and may be expressed as the product of the length of the station interval times that probable error in the gradient. Conversely, the probable error of the gradient may be expressed as the quotient of the probable error in terms of $\Delta g$ over the station interval divided by the length of the station interval. If the terms

$$\frac{\overline{EC}^2}{N}$$

of formula (7) are weighted in terms of the square of the reciprocal of the length of the station interval, $SI$, to read

$$\frac{\overline{EC}_1^2}{N_1\overline{SI}_1^2}, \quad \frac{\overline{EC}_2^2}{N_2\overline{SI}_2^2}, \quad \frac{\overline{EC}_n^2}{N_n\overline{SI}_n^2}$$

the errors of the torsion balance surveys, then, are expressed in terms of gradient and not of $\Delta g$ and the probable error of the torsion balance measurements will be in terms of gradient. But

$SI = \dfrac{L}{N}$ and the other terms $\dfrac{\overline{EC}^2}{N \cdot (SI)^2}$ can be written:

$$\frac{\overline{EC}^2}{N\dfrac{L^2}{N^2}} \quad \text{or} \quad \frac{N \cdot \overline{EC}^2}{L^2}.$$

If the terms $\dfrac{\overline{EC}^2}{N}$ of formula (7) are replaced by $\dfrac{N \cdot \overline{EC}^2}{L^2}$ formula (5) is obtained, which gives the probable error in the torsion balance observations in terms of gradient; that is, in Eötvös units, although the observed errors are in terms of $\Delta g$; that is, of cm. sec.$^{-2}$

Formula (5) involves the two assumptions, first, that the error in calculation of $\Delta g$ over a station interval is a linear function of the length of the station interval and of the error in the gradient and, second, that the error is independent of the magnitude of the gradient. Neither assumption is exactly true but in the present study no attempt has been made to analyze that more complicated variation of the error of torsion balance measurements.

The original data and the calculated values of

$$\frac{EC^2 \cdot N}{L^2}$$

are given in Table I.

The "probable error" of the determination of the gradient at those twenty-eight hundred odd stations, therefore, is of the general magnitude of $\pm 2.2$ *E*, but the "probable error" of the determination of the gradient may be different in different areas. If the surveys of Table I are grouped by the length of the interval between stations, the "probable error" of the gradient varies considerably between groups. The various "probable errors" are given in Table II. They range from $\pm 1.5$ *E* to $\pm 5.0$ *E*. The corresponding "probable error" in the individual traverses must have a yet higher range. The figure, $\pm 2.2$ *E*, therefore, itself has a large "probable error" and only its general magnitude is of significance. Intuitively, the writer for years has estimated the common error of torsion balance observations of the gradient in the Gulf Coast region as of the magnitude of 1.5 to 2.5 *E*.

TABLE I

ORIGINAL DATA AND CALCULATED VALUES OF $\frac{EC^2N}{L^2}$

| Error of Closure EC in $10^{-4}$ Cm. Sec.$^{-2}$ | Number of Stations N | Length of Traverse L in Km. | $\frac{EC^2N}{L^2}$ | Error of Closure EC in $10^{-4}$ Cm. Sec.$^{-2}$ | Number of Stations N | Length of Traverse L in Km. | $\frac{EC^2N}{L^2}$ |
|---|---|---|---|---|---|---|---|
| 7.6 | 71 | 38.4 | 2.8 | 2.0 | 30 | 11.6 | 0.9 |
| 3.8 | 72 | 45.1 | 0.5 | 2.9 | 90 | 32.0 | 0.7 |
| 11.4 | 37 | 19.5 | 12.6 | 7.6 | 65 | 25.9 | 5.8 |
| 7.6 | 44 | 30.5 | 2.7 | 11.4 | 178 | 28.3 | 29.0 |
| 11.4 | 45 | 36.0 | 5.2 | 2.4 | 201 | 105.2 | 1.0 |
| 11.4 | 51 | 29.6 | 7.6 | 8.0 | 75 | 41.1 | 2.9 |
| 7.6 | 56 | 28.7 | 4.0 | 3.0 | 102 | 23.1 | 1.7 |
| 7.6 | 64 | 36.6 | 2.9 | 5.0 | 97 | 21.3 | 5.4 |
| 0 | 123 | 37.2 | 0 | 8.0 | 64 | 14.0 | 21.0 |
| 3.8 | 65 | 19.5 | 0.2 | 6.0 | 80 | 19.5 | 0.7 |
| 7.6 | 82 | 23.2 | 8.9 | 5.0 | 81 | 24.4 | 3.4 |
| 7.6 | 73 | 22.6 | 8.3 | 7.6 | 61 | 35.6 | 2.8 |
| 13.3 | 201 | 69.5 | 7.4 | 15.2 | 79 | 43.6 | 9.6 |
| 36.1 | 164 | 65.5 | 50.5 | 11.4 | 56 | 28.0 | 9.3 |
| 36.1 | 171 | 53.9 | 76.5 | 3.8 | 24 | 11.3 | 2.2 |
| 5.7 | 64 | 27.4 | 2.8 | 5.7 | 36 | 17.0 | 4.1 |
| 4.8 | 50 | 13.4 | 6.4 | 1.9 | 39 | 17.7 | 0.4 |
| 8.0 | 79 | 58.5 | 1.5 | 5.7 | 32 | 15.5 | 4.4 |
| 4.8 | 26 | 3.0 | 66.5 | 13.3 | 130 | 72.2 | 4.4 |
| 1.6 | 35 | 4.9 | 3.8 | 7.6 | 113 | 51.8 | 2.4 |
| 1.6 | 38 | 4.6 | 4.7 | 17.1 | 100 | 48.9 | 12.3 |
| 4.8 | 71 | 9.4 | 18.5 | 0 | 62 | 37.6 | 0 |
| $n=45$ $PE_{U_n}=0.6745\sqrt{418.7\cdot45}=2.2E$ | | | | 0 | 349 | 143.8 | 0 |
| | | | | | | | 418.7 |

TABLE II

PROBABLE ERROR OF THE DETERMINATION OF THE GRADIENT IN SURVEYS WITH DIFFERENT STATION INTERVALS

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Station interval in meters.... | 150 | 300 | 400 | 500 | 600 | 700 | 800 |
| Number of traverses........ | 5 | 12 | 8 | 12 | 6 | 2 | 1 |
| Probable error............. | ±5.0 | ±3.4 | ±2.8 | ±1.9 | ±1.9 | ±1.5 | ±2.3 |

TABLE III

PROBABLE ERROR OF DETERMINATION OF $\Delta g$ BETWEEN PLACES BY GOOD TORSION BALANCE SURVEYS IN $10^{-4}$ DYNES (0.1 MILLEDYNE)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Distance between places in kilometers. | 1 | 5 | 10 | 20 | 40 | 80 | 100 |
| Probable error of: single direct traverse; or single traverse distance measured along traverse; or two more or less indirect traverses..... | ±12 | ±3 | ±4 | ±6 | ±8 | ±11 | ±13 |
| Several traverses.................. | ±0.8 | ±2 | ±3 | ±4 | ±6 | ±8 | ±9 |

That "probable error," $\pm 2.2\ E$, is the composite error of a considerable number of factors. It arises: (a) from all instrumental errors in the determination of the crude gradient at the station, (b) from all errors in applying corrections to the crude gradient, (c) from errors in plotting gradient arrows on the map and from the crudeness of gradient arrows on a scale of 1 mm.$=E$ as the starting point for the calculation of relative gravity, (d) from inaccuracy in the use of the writer's method of calculating relative gravity, and (e) from error arising from the fact that the interval between stations is not sufficiently close to give a true picture of the variation of the gradient. It probably also varies with the magnitude of the gradient; the data are not sufficient to study that variation. An actual error five times the "probable error" should occur once in one thousand times, according to the theory of the "probable error." Divergent gradients which depart vectorially much more than $5\times\pm 2.2\ E$ are moderately common. Such plainly aberrant gradient arrows were disregarded by the geophysicist in the calculation of relative gravity in the traverses from which the data of Table I were taken, and their weight, therefore, was not felt in the calculation of that "probable error."

The "probable error" of the determination of relative gravity by good torsion balance surveys can be stated in a simpler and more practical form. The "probable error" of the determination of relative gravity by the torsion balance can be controlled within certain limits by variation of the station interval. Formula (3) can be rewritten:

$$\text{from: } PE = \sqrt{n}\cdot pe \qquad (8)$$

$$\text{to: } PE_{\Delta g} = \sqrt{n}\cdot SI\cdot pe_{U_{xz}} = \frac{L}{\sqrt{n}} pe_{U_{xz}}$$

for the special case of the torsion balance. If the number of stations in a traverse of constant length is varied as the square of the variation of the "probable error" of the individual observations, the "probable error" of the determination of $\Delta g$ for the traverse remains constant. In practice in good torsion balance surveys, the station interval between stations is decreased in areas of irregular and erratic gradient arrows and is increased in areas of consistent gradient arrows. The "probable error" of good ordinary torsion balance surveys in practice, therefore, should be independent of the station interval and should vary as the square root of the length of the traverse. If $(SI\cdot pe_{U_{xz}})$ in formula (8) is maintained constant, then $(n)$ will vary directly with the length of the traverse, and $PE_{\Delta g}$ will vary as the square root

of the length of the traverse. As $SI \cdot pe_{U_{zz}}$ somewhat commonly in practice is held approximately constant, the "probable error" of the determination of $\Delta g$ by ordinary good torsion balance surveys can be expressed in terms of $\Delta g$ per some standard length of traverse.

That this is so, can be seen by analysis of the error of closure of those 45 traverses. The error of closure of each closure of $\Delta g$ in each of those traverses can be scaled up or down by the formula

$$EC_{10} = \sqrt{\frac{10}{L}} \cdot EC \tag{9}$$

to the error of closure ($EC_{10}$), which the traverse would have had, if its length had been 10 kilometers instead of ($L$) kilometers, and if there had been no change in the station interval. The resulting errors of closure per 10-kilometer traverses have been sorted by length of the station interval and are given in Table IV. The respective errors of closure and the respective "probable errors" of $\Delta g$ for the traverses of 100, 200, 300, 400, 500, 600 meters station interval, can be seen to

TABLE IV

ERRORS OF CLOSURE SCALED TO A 10 KM. LENGTH OF THE TRAVERSE

| *Station interval in meters* | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 |
|---|---|---|---|---|---|---|---|---|
| Error of closure of $\Delta g$ in $10^{-4}$ dynes | 8.7 | 6.8 | 15.6 | 14.1 | 8.2 | 7.3 | 4.3 | 6.0 |
| | 4.9 | 6.8 | 5.0 | 5.0 | 7.7 | 6.6 | 3.3 | |
| | 3.4 | 4.3 | 5.0 | 4.7 | 6.8 | 4.9 | | |
| | 2.3 | 3.4 | 4.1 | 3.4 | 4.5 | 4.0 | | |
| | | 2.0 | 3.2 | 1.9 | 4.4 | 4.0 | | |
| | | | 2.7 | 1.6 | 3.9 | 1.8 | | |
| | | | 0.0 | | 3.9 | 0.0 | | |
| | | | | | 3.6 | 0.0 | | |
| | | | | | 3.3 | | | |
| | | | | | 1.6 | | | |
| | | | | | 1.4 | | | |
| "Probable error" of traverse.......... | ±3.6 | ±3.4 | ±4.6 | ±4.4 | ±3.4 | ±3.2 | | |

"Probable error" for all 45 traverses: ±3.9

be independent of the length of the station interval. That "probable error" ranges only from 0.32 milledyne for the traverses with a station interval of approximately 600 meters to 0.46 milledyne for the traverses of approximately 300 meters; and for the traverses of approximately 100, 200, 500, and 600 meters length, that "probable error" ranges only from 0.32 to 0.36 milledyne. The "probable error" of the individual observations, however, was considerably larger in the traverses

with the shorter station interval (Table II). That larger "probable error" of the individual observations in the traverses with the shorter station interval has been compensated by the use of that shorter station interval; and the "probable error" of the traverse as a whole is no greater for those traverses with the shorter station interval than for those with the longer station interval. The "probable error" of determination of relative gravity by those 45 traverses is 0.4 milledyne per 10 kilometers of traverse without regard to the station interval; and the actual error of closure, with two exceptions, is less than 0.9 milledyne and with only five exceptions, is less than 0.75 milledyne per 10 kilometers of traverse without regard to the station interval.

The "probable error" of the determination of relative gravity between two places by torsion balance surveys depends in part on the number of torsion balance traverses which connect the two places, decreasing inversely as the square of the number of equally good traverses. Key places in torsion balance surveys in general are connected by at least two traverses, and in many surveys are connected by a net of traverses. Different weights in general should be given the different traverses in the calculation of the relative gravity between the two places and in the calculation of the "probable error" of that determination of the relative gravity. But that "probable error" in practice probably will be $1/\sqrt{2}$ to $1/\sqrt{3}$ times the "probable error" of the determination of the relative gravity by a single traverse. The "probable error" of the determination of relative gravity between key places within the surveys of those 45 traverses, therefore, should be ($1/\sqrt{2}$ to $1/\sqrt{3}$) times 0.4 milledyne or 0.30 to 0.25 milledyne for places 10 kilometers apart along the route of the torsion balance traverses. For an airline distance of 10 kilometers between the two places, the corresponding "probable error" in practice should be 0.7 to 1.0 times the "probable error" of the determination of $\Delta g$ by an airline torsion balance traverse between the two places and, therefore, should be 0.3 to 0.4 milledyne.

Shrewd adjustment of errors in those 45 traverses presumably has reduced the "probable error" of those determinations of relative gravity below the figures of the preceding paragraph. The error of closure in $\Delta g$ in torsion balance traverses commonly is caused not only by the cumulative effects of small, or moderately small, errors at each set-up but also by a few large errors. A skilled interpreter commonly can recognize the weak spots in which those errors are mostly likely to have come in; by disregarding or adversely weighting

the effect of single seriously abnormal gradient arrows, or less commonly, pairs of gradient arrows, he attempts to eliminate such errors in the first calculation of relative gravity; in the subsequent adjustment of the traverse or traverses, somewhat commonly much of the error of closure may be eliminated by a slight change in his weighting of those few irregular gradient arrows. The variation of the gradient from station to station in many places is not linear and the geophysicist has a certain latitude in his subjective estimation of the probable variation of gravity between the two stations. The error of closure in many traverses can be almost eliminated by taking those slightly different alternative choices in the spacing and the running of the isogams. The subjective weighting of observations, of course, is open to danger of error and in the hands of an inexpert geophysicist, leads to much more erroneous results than the automatic mathematical distribution and adjustment of the error. But the writer believes that the expert interpreter can obtain better accuracy by exercising subjective judgment in throwing as much of the errors of closure as possible into the weak places in lines rather than by automatic mathematical distribution of the errors. The "probable error" of the determination of relative gravity in those 45 traverses presumably, therefore, is slightly less than $\pm 0.25$ milledyne per 10 kilometers of double traverse and less than $\pm 0.35$ milledyne between places 10 kilometers apart, airline distance.

That "probable error," 0.25 milledyne per 10 kilometers of double traverse or 0.35 milledyne per 10 kilometers of airline distance, presumably is characteristic of most good torsion balance surveys in what a torsion balance operator would call good, fair, and slightly poor torsion balance terrane. Those 45 traverses lay in all types of terrane in the Gulf Coastal Plain of Texas and Louisiana and a few of them were on the llanos of Venezuela and elsewhere than in the Gulf Coastal Plain. Less than one-fourth of the traverses were in the Coastal Prairies of Texas and Louisiana, which are especially favorable for a low "probable error" of observation. The 45 traverses, therefore, are fairly characteristic of torsion balance work in areas which are commonly regarded as good, fair, or slightly poor for torsion balance observations. Mathematically the same grade of accuracy could be maintained by use of a sufficiently close net of stations to compensate the "probable error" in the individual observations, but the number of stations necessary increases as the square of the increase in the "probable error" of the individual ob-

servations, and, therefore, the cost and tediousness of too close a net of stations puts a practical limit to the maintenance of that accuracy of $\pm 0.35$ milledyne between places 10 kilometers apart, airline distance, or for the maintenance of any particular grade of accuracy. In reconnaissance in oil work, a station interval less than 250 meters commonly is impracticable, and if the "probable error" of the individual gradient observations rises above $\pm 2$ *E*, it becomes impracticable to maintain an accuracy of $\pm 0.35$ milledyne in the determination of relative gravity between places approximately 10 kilometers apart, airline distance. In some areas in South Texas, in which the caliche lies close to the surface, the "probable error" of individual observations probably is greater than $\pm 7$ *E;* and in certain areas in East Texas, the "probable error" of individual observations probably is greater than $\pm 5$ *E*. The "probable error" of the determination of gravity between two places approximately 10 kilometers apart in such areas will be very much greater than $\pm 0.35$ milledyne.

Knowledge of the "probable error" of the determination of $\Delta g$ by torsion balance surveys is important in certain types of combinations of torsion balance and pendulum surveys. According to a rather common suggestion from "pure" geophysicists, pendulum observations of relative gravity at a net of key stations should be used to provide a framework of accurate gravity benchmarks to which the supposedly less accurate torsion balance surveys would be tied and adjusted. But the accuracy of the torsion balance surveys will be increased thereby only if the "probable error" of the determination of relative gravity by the pendulum between two stations is less than that by the torsion balance surveys. The determination of relative gravity by the relative pendulum is independent of the distance between stations; the value of $\Delta g$ between two stations is simply the difference between the observed values of relative gravity at the two stations, and the "probable error" of $\Delta g$ between the two stations is the square root of the sum of the squares of the respective "probable errors" of the individual observations. The "probable error" of the determination of $\Delta g$ between two places by good torsion balance surveys varies, in practice, with the square root of the distance between the two places. The torsion balance surveys will measure $\Delta g$ more accurately than the pendulum if the two stations can be connected by very short torsion balance traverses, and the pendulum will measure $\Delta g$ more accurately than the torsion balance if the two stations can be connected only by very long torsion balance traverses.

If the pendulum stations are placed closer together than a certain minimum distance, the "probable error" or the pendulum determination of $\Delta g$ between adjacent stations will be greater than the "probable error" of the torsion balance determination of that $\Delta g$; and adjustment of the torsion balance survey to the pendulum values of $\Delta g$ will decrease the accuracy of the torsion balance survey. If the distance between the adjacent pendulum stations is greater than that minimum distance, the "probable error" of the pendulum determination of $\Delta g$ between adjacent stations will be less than that of the torsion balance determination; and the accuracy of the torsion balance survey will be improved by adjusting its results to the pendulum results.

The accuracy of the determination of relative gravity by the relative pendulum varies. The "probable error" of the pendulum observations of the latter part of the past century presumably was, in general, many milledynes. The probable error of the observations of the recent past in general has been $\pm 1$ milledyne, although a few poorer but acceptable stations have had a "probable error" of $\pm 2$ milledynes. The better modern observations are reported to have a "probable error" of $\pm 0.3$ to $\pm 0.5$ milledyne. The geophysical department of one oil company asserts that its pendulums are reoccupying stations with a "probable error" of observation less than $\pm 0.1$ milledyne. The "probable error" of the determination of the elevation or relative elevation of the pendulum station is relatively unimportant in connection with the pendulum observations whose "probable error" is $\pm 1$ milledyne or more, but is, of course, of very considerable importance in connection with observations whose "probable error" is less than $\pm 0.3$ milledyne, for the variation of $(g)$ with elevation is $\pm 0.308$ milledyne per meter. The "probable error" in feet of first class (but not precise) levelling is approximately $\pm 0.05$ (number of miles), but only 1.5 miles of closed traverse, or 3 miles of unrepeated traverse can be run per day in levelling of that accuracy and, therefore, most commercial levelling in connection with commercial geophysical work probably will be speedier and less accurate and its "probable error" may have to be taken seriously into account. The "probable error" of the station determination of gravity will be the square root of the sum of the square of the "probable error" of the pendulum determination of gravity, plus the square of the "probable error" of the determination of the elevation. The "probable error" of the determination of $\Delta g$ between two places will be the sum of the

squares of the respective "probable errors" of the two pendulum observations and of the two determinations of the elevation. The "probable error" of the pendulum determination of gravity at each key station can be decreased by reoccupation of that station or by the occupation of additional closely adjacent stations which are tied together by torsion balance determinations of the value of $\Delta g$ between the key station and each of the subsidiary stations. The decrease in the "probable error" will vary as the reciprocal of the square root of the number of stations.

The minimum interval between pendulum observations which are to supplement ordinary, good torsion balance surveys in good, fair, or even slightly poor torsion balance terrane is given in Table V.

TABLE V

MINIMUM INTERVAL AT WHICH PENDULUM OBSERVATIONS SHOULD BE USED TO TORSION BALANCE SURVEYS

| | *"Probable Error" of Torsion Balance Determination of $\Delta g$ in $10^{-4}$ Dynes for Places 10 Km. Apart Airline Distance* | | *"Probable Error" of Pendulum Determination of $\Delta g$ in $1 \times 10^{-4}$ Dynes* | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $\pm 10$ | | $\pm 5$ | | $\pm 2\frac{1}{2}$ | | $\pm 1$ | |
| | | | *Interval in Kilometers* | | | | | | | |
| | *A** | *B* | *A* | *B* | *A* | *B* | *A* | *B* | *A* | *B* |
| Poorer "Good" surveys...... | 7 | 5 | 40 | 75 | 10 | 20 | $2\frac{1}{2}$ | 5 | 0.3 | 0.5 |
| Average "Good" surveys...... | 4 | 3 | 120 | 220 | 30 | 55 | 8 | 14 | 1.0 | 1.5 |
| Better "Good" surveys...... | 2 | $1\frac{1}{2}$ | 500 | 650 | 120 | 210 | 30 | 55 | 4.5 | 6 |

* *A*. The two places are connected by a single direct or two indirect torsion balance traverses.
*B*. The two places are connected by several traverses.

In surveys primarily by the pendulum, or in pendulum surveys which are supplemented by sketchy torsion-balance surveys, the intervals between the pendulum stations very much less than the minimum intervals of Table IV may be used in order to increase the accuracy of the survey.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1250-1259, 3 FIGS.

# CURVATURE OF EQUIPOTENTIAL SURFACES[1]

M. M. SLOTNICK[2]
Houston, Texas

## ABSTRACT

If one is to have a complete and satisfying understanding of the theory of the torsion balance, it is essential to have clearly in mind a physical picture of the quantities involved. Most authors assume either that their readers are well versed in the differential geometry of surfaces in a Euclidean three-dimensional space or that a discussion of surface curvature is far beyond the reader's ability to grasp. Too often is neither of these true. The writer attempts to present a mathematical discussion of this matter in which only the bare fundamental concepts of the differential calculus are needed.

## INTRODUCTION

In this paper, the writer attempts to develop the mathematical theory of the curvature of the equipotential surfaces due to the gravitational field, with the purpose of producing a clear "physical" picture of this quantity. It is the writer's impression that such a development, although fundamental to the mathematician, is lacking in the usual torsion balance literature available to the geophysicist. Our goal is to find the curvature relations used in torsion balance work. The mathematical needs for this subject are not too great—and for further simplification, the demands of mathematical rigor are, at times, sacrificed in this paper.

## DEFINITIONS

Consider an arbitrary point $P$ on a surface $S$, which is "smooth" in the neighborhood of $P$ in the sense that the equation of $S$ may be expressed as a series when the surrounding space is referred to a convenient cartesian coördinate system. The *tangent plane* to $S$ at $P$ is that plane in which all the lines tangent to $S$ at $P$ lie. The straight line perpendicular to this plane at $P$ is the *normal* to the surface $S$ at that point.

## COÖRDINATE SYSTEM

We now proceed to choose, as is our privilege, a coördinate system in such a manner that the mathematical work involved is materially

[1] Read before the Association at the Oklahoma City meeting, March 25, 1932.

[2] Geophysics department, Humble Oil and Refining Company. Introduced by L. W. Blau.

simplified. Let the normal to $S$ at $P$, oriented in either of its directions, be the $z$ axis. In the tangent plane to $S$ at $P$ let any two mutually perpendicular lines be chosen as the $x$ and $y$ axes. Both of these axes are obviously perpendicular to the $z$ axis. Let us also point out

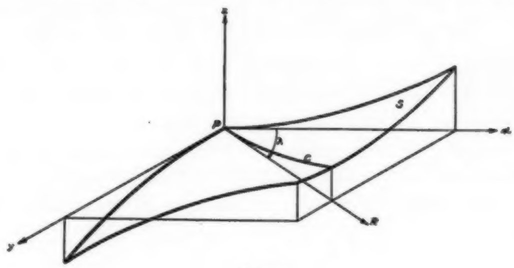


FIG. 1

that the tangent line at $P$ to any curve on $S$ passing through $P$ lies in the $(x, y)$ plane. The situation thus far described is schematically shown in Figure 1, where, for convenience, only part of the surface $S$ in the neighborhood of $P$ is indicated.

### EQUATION OF $S$

Suppose that the equation of $S$, referred to the chosen coördinate system, is

$$z = z(x, y), \tag{1}$$

and that this expression is expanded in series about $P$; that is,

$$z = a + (px + qy) + \tfrac{1}{2}(rx^2 + 2sxy + ty^2) + \cdots, \tag{2}$$

where

$$p = \frac{\partial z}{\partial x}, \qquad q = \frac{\partial z}{\partial y},$$

$$r = \frac{\partial^2 z}{\partial x^2}, \quad s = \frac{\partial^2 z}{\partial x \partial y}, \quad t = \frac{\partial^2 z}{\partial y^2},$$

the values of these derivatives being taken at the point $P$, whose coördinates are, of course, (0, 0, 0). The series (2) has been written only to the second order terms, which are all that are required.

Since the surface $S$ passes through $P$:(0, 0, 0), equation (2) must be satisfied by its coördinates. Accordingly, $a = 0$. Again, the slope of the curve on $S$ at $P$, which is the section of the surface made by

the $(x, z)$ plane, is the value of $p$ there, and consequently this is zero. Similarly, $q=0$. Thus, by virtue of our choice of axes, the series (2) reduces to

$$z = \tfrac{1}{2}(rx^2 + 2sxy + ty^2) + \cdots. \tag{3}$$

CURVATURE OF A PLANE SECTION OF $S$ AT $P$

Let $C$ be the curve of intersection of any plane $zPR$ through the $z$ axis with the surface $S$, and let the angle between this plane and the $(x, z)$ plane be $\lambda$. Obviously, then, the curve $C$ is a plane curve and $PR$, the tangent line to it at $P$, lies in the $(x, y)$ plane, with the angle $xPR$ equal to $\lambda$. The lines $Pz$ and $PR$ are at right angles to each other, and we choose these lines as coördinate axes in their plane $zPR$. Since

$$x = R\cos\lambda, \quad y = R\sin\lambda, \tag{4}$$

the equation of $C$ in terms of the coördinates $(R, z)$ is, by virtue of (3):

$$z = \tfrac{1}{2}R^2(r\cos^2\lambda + 2s\sin\lambda\cos\lambda + t\sin^2\lambda) + \cdots. \tag{5}$$

We recall at this stage the theorem of the elementary differential calculus that the curvature of the curve whose equation is $y=f(x)$ at a point is the value of

$$k = \frac{\dfrac{d^2y}{dx^2}}{\left[1 + \left(\dfrac{dy}{dx}\right)^2\right]^{3/2}} \tag{6}$$

at that point. In equation (5), $z$ is expressed as a function of $R$, and, at $P$, $z=R=0$. The quantities $r$, $s$, $t$ are constants, inasmuch as they represent the values of the second derivatives of $z$ with respect to $x$ and $y$ at $P$; and $\lambda$ is a constant for the particular section $C$ chosen. Consequently, the curvature of $C$ at $P$ is the value of

$$k = \frac{\dfrac{d^2z}{dR^2}}{\left[1+\left(\dfrac{dz}{dR}\right)^2\right]^{3/2}}, \tag{7}$$

when $z=R=0$.

Differentiating (5), we obtain

$$\frac{dz}{dR} = R(r\cos^2\lambda + 2s\sin\lambda\cos\lambda + t\sin^2\lambda) + \cdots, \tag{8}$$

and

$$\frac{d^2z}{dR^2} = (r\cos^2\lambda + 2s\sin\lambda\cos\lambda + t\sin^2\lambda) + \cdots. \tag{9}$$

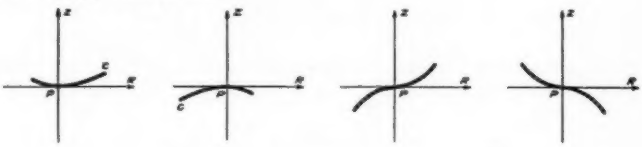
The terms of each of these series beyond those written involve $R$ to at least the first power. At $P$, then, where $z=R=0$,

$$\frac{dz}{dR} = 0, \quad \frac{d^2z}{dR^2} = r\cos^2\lambda + 2s\sin\lambda\cos\lambda + t\sin^2\lambda. \tag{10}$$

It is these values, as we have seen, that we must use in (7) to obtain the curvature of $C$ at $P$, and substituting these, we have

$$k = r\cos^2\lambda + 2s\sin\lambda\cos\lambda + t\sin^2\lambda. \tag{11}$$

In ordinary work in the elementary differential calculus, the value of the curvature of a curve at a point is taken as the absolute value of (6) and no attention is paid to the fact that the numerator, $\frac{d^2y}{dx^2}$, may be negative as well as positive. However, in surface theory, the algebraic value of the curvature is important, and our definition of the curvature of the plane section $C$ of the surface $S$ at the point $P$, as embodied in (7), places due regard on the *algebraic* value of $\frac{d^2z}{dR^2}$. We append a schematic series of figures here to show, somewhat more clearly, what is meant.



2a 2b 2c

FIG. 2

Figure 2*a* indicates the form of the curve $C$ in the neighborhood of $P$, if, for the value of $\lambda$ defining $C$, $\frac{d^2z}{dR^2}>0$. Figure 2*b* indicates the same thing if $\frac{d^2z}{dR^2}<0$. Finally, if for that value of $\lambda$ defining $C$, $\frac{d^2z}{dR^2}=0$ and $\frac{d^3z}{dR^3}\neq 0$ at $P$, the form of $C$ is as shown in one or the other of the figures 2*c*.

VARIATION OF CURVATURE WITH $\lambda$

Equation (11) expresses the algebraic value of the curvature at the point $P$ of that plane normal section $C$ of the surface $S$, made by the plane through the $z$ axis whose angle with the $(x, z)$ plane is $\lambda$. Varying the value of $\lambda$ from $0°$ to $180°$ continuously corresponds to twisting the normal plane continuously around the $z$ axis from the $(x, z)$ plane, $(\lambda=0°)$, through its position of coincidence with the $(y, z)$ plane, $(\lambda=90°)$, and finally back to the $(x, z)$ plane for which $\lambda=0°$ or $180°$ (from $180°$ to $360°$, the sections obtained as $\lambda$ varies from $0°$ to $180°$ are repeated).

The first fact to notice is that if for all values of $\lambda$ from $0°$ to $180°$, the curvature (11) is always positive, or always negative, the surface in the neighborhood of $P$ lies on one side of its tangent plane. If, however, as $\lambda$ varies in this range, the curvature changes sign, part of the surface lies on one side of the tangent plane to $S$ at $P$ and part on the other. The latter situation is the one shown schematically in Figure 1.

Suppose that we fix our attention to the curvature $k_1$ at $P$ of the section for which $\lambda=\lambda_1$; that is,

$$k_1 = r\cos^2\lambda_1 + 2s\sin\lambda_1\cos\lambda_1 + t\sin^2\lambda_1. \tag{12}$$

Consider the curvature $k_2$ at the same point, of the section whose plane is at right angles to that of the first section; that is, that for which $\lambda=\lambda_2=\lambda_1\pm 90°$. Substituting this value for $\lambda$ in (11) yields:

$$k_2 = r\sin^2\lambda - 2s\sin\lambda\cos\lambda + t\cos^2\lambda. \tag{13}$$

The sum of (12) and (13) is:

$$k_1 + k_2 = r + t, \tag{14}$$

a constant. To put this interesting result in words: *The algebraic sum of the curvatures at a non-singular point of an analytic surface of any two normal plane sections at right angles to each other is constant.* One-half of this constant is called the *mean curvature* of the surface at the point.

The next question to be raised in regard to (11) is whether, as $\lambda$ varies from $0°$ to $180°$, the curvature $k$ reaches extreme (maximum and minimum) values; and, if so, for what values of $\lambda$? A maximum or minimum value of $k$ is obtained whenever $\dfrac{dk}{d\lambda}=0$ and $\dfrac{d^2k}{d\lambda^2}\neq 0$.

Differentiating (11), we obtain:

$$\frac{dk}{d\lambda} = (t - r)\sin 2\lambda + 2s\cos 2\lambda. \tag{15}$$

If this derivative is set equal to zero, and solved for $\lambda$, we find:

$$\tan 2\lambda = \frac{2s}{r - t}.* \tag{16}$$

There are two values of $\lambda$ lying between 0° and 180° which satisfy equation (16), and their difference is 90°.[1] That is to say, if $\lambda_1$ is one solution of (16) lying in value between 0° and 180°, then $\lambda_1 \pm 90°$ is

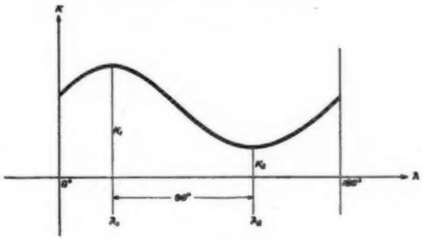


FIG. 3

the other, that one being chosen which lies in value in the same range. This result may be stated in the form of a theorem: *At every non-singular point (not umbilical) of an analytic surface there are two normal sections of the surface, at right angles to each other, for which the curvatures attain extreme values.*

Combining this theorem with the preceding one, in which we have seen that the sum of the curvatures for two normal sections at right angles to each other is a constant (*cf.* (14)), we must conclude that at one of these sections the curvature is a maximum and at the other it is a minimum.

* To show that $d^2k/d\lambda^2 \neq 0$ when $dk/d\lambda = 0$, we note that, since

$$\frac{d^2k}{d\lambda^2} = 2\cos 2\lambda\left[(t - r) - 2s\tan 2\lambda\right],$$

its value when $dk/d\lambda = 0$ is obtained by substituting the value of $\lambda$ of equation (16) in this last equation. After simplification, this reduces to

$$\pm\, 2\sqrt{(r - t)^2 + 4s^2},$$

which can vanish when and only when $r = t$ and $s = 0$. A point at which this occurs is an *umbilical* point; and, referring back to equation (11), we see that the curvatures of the normal sections to a surface at a point of this type are all equal. Such points will be excluded from this discussion.

[1] If $r = t$ and $s \neq 0$, the values of $\lambda$ are 45° and 135°.

If the curvatures $k$ of the plane normal sections be plotted against $\lambda$ for $0° \leqq \lambda < 180°$, the curve would have the characteristic form shown in Figure 3. If the curvature changes sign, as $\lambda$ varies, the corresponding curve crosses the $\lambda$-axis twice.

It has been shown that the difference in the values of $\lambda$ for which $k$ is a maximum and that for which it is a minimum is 90°. Moreover, the algebraic sum of the ordinates ($k$) for any two values of $\lambda$ whose difference is 90° is a constant.

The directions on the surface at $P$ in which these extreme values of the normal curvature occur are called the ***principal directions***. The reciprocals, $\rho_1$ and $\rho_2$, of the extreme values of the curvatures, $k_1$ and $k_2$, are called the ***radii of principal curvatures:***

$$k_1 = \frac{1}{\rho_1}, \quad k_2 = \frac{1}{\rho_2} \cdot$$

The ***total*** or ***Gaussian curvature*** of the surface at the point is defined as the product $k_1k_2$; and one-half the sum: $\frac{1}{2}(k_1+k_2)$ is the ***mean curvature*** of the surface at the point.

Many further interesting properties of the curvature of a surface can readily be deduced from the analytical method here developed. However, it is not necessary for our purpose to delve into these. It is well to point out before leaving the matter, that, though, initially, we chose the $x$ and $y$ axes as any two mutually perpendicular lines in the tangent plane to $S$ at $P$, we may now, in the light of our results, choose them in the two principal directions. Analytically, this means that the solutions of (16) are $\lambda = 0°$ and $\lambda = 90°$; that is, $s = 0$ in the series expansion (3).

The equation (16) leads to the results:

$$\sin 2\lambda = \frac{\pm 2s}{w}, \quad \cos 2\lambda = \frac{\pm (r - t)}{w}, \tag{17}$$

where

$$w = \sqrt{(r - t)^2 + 4s^2}. \tag{18}$$

The positive signs in (17) yield the value of $\lambda$ for which the curvature attains one extreme value, and the negative signs yield the other value of $\lambda$, differing from the first by 90°, for which the curvature attains the other extreme value. If we set either one of these values of $\lambda$ for $\lambda_1$ in (12) and (13), the $k_1$ and $k_2$ so obtained will be the values of these extreme curvatures.

Let us note that the difference of equations (12) and (13) may be written

$$(19) \qquad k_1 - k_2 = (r - t)\cos 2\lambda + 2s \sin 2\lambda,$$

and, using the results of (17), we find that the extreme curvatures satisfy the relation

$$(20) \qquad k_1 - k_2 = \pm \left[ \frac{(r - t)^2 + 4s^2}{w} \right] = \pm\, w.\text{*}$$

APPLICATION TO EQUIPOTENTIAL SURFACES

The torsion balance deals with the equipotential surfaces, which are the surfaces perpendicular to the lines of force of the earth's gravitational field. Let the equation of the equipotential surface through the center of gravity of the suspended system of a torsion balance be

$$(21) \qquad U(x, y, z) = \text{constant},$$

with respect to the usual coördinate system used; namely, the $z$ axis is the direction of the force of gravity at the center of gravity of the suspended system (taken as the origin) directed positively downward, the $x$ and $y$ axes are the lines through the origin, tangent to the equipotential surface, bearing north and east respectively. The value of gravity at the point is, then,

$$(22) \qquad g = \frac{\partial U}{\partial z}\,\cdot$$

The torsion balance observes the values of

$$(23) \qquad \frac{\partial^2 U}{\partial x \partial z} = \frac{\partial g}{\partial x}, \quad \frac{\partial^2 U}{\partial y \partial z} = \frac{\partial g}{\partial y},$$

and

$$(24) \qquad U_\Delta = \frac{\partial^2 U}{\partial y^2} - \frac{\partial^2 U}{\partial x^2}, \quad U_{xy} = \frac{\partial^2 U}{\partial x \partial y},$$

* It will be noticed that the mathematical analysis does not differentiate between $k_1$ and $k_2$, as to which is the maximum and which the minimum, and cannot do so. This becomes obvious when we consider that if, initially, the $z$ axis had been oriented in the opposite direction, as it well might have, the maximum curvature would become the minimum and vice versa. This corresponds with a reflection of the curve of Figure 3 in the $\lambda$-axis; for what was originally $z$ is now $-z$ and the equation (10) changes sign. In short, equation (20) states that the numerical value of the difference between the principal curvature is $w$. In the numerical work used in torsion balance calculations, however, the curvatures assume, tacitly, numerical algebraic values and the corresponding $\lambda$ to each of these can be assigned. This will be indicated briefly in the last paragraph of the paper.

at the point in question. The first pair of equations deals with the gradient of gravity and those of the latter pair are referred to as the curvature quantities.

Our problem is to find the values of $p$, $q$, $r$, $s$, and $t$ for our surface defined in the form (21). This equation defines $z$ implicitly as a function of the two independent variables $x$ and $y$. Recalling that the center of gravity of the suspended system bears the same relation to the equipotential system through it as does the point $P$ to the surface $S$ previously described, we conclude that

$$\frac{\partial z}{\partial x} = p = 0, \text{ and } \frac{\partial z}{\partial y} = q = 0.$$

Since, however,

$$\frac{\partial U}{\partial x} + \frac{\partial U}{\partial z}\frac{\partial z}{\partial x} = 0, \quad \frac{\partial U}{\partial y} + \frac{\partial U}{\partial z}\frac{\partial z}{\partial y} = 0,^{*} \tag{25}$$

it follows that at the origin, $\dfrac{\partial U}{\partial x} = \dfrac{\partial U}{\partial y} = 0$.

Similarly, since at the origin, $p = q = 0$, we find that

$$\begin{aligned} &\text{a.} \quad \frac{\partial^2 U}{\partial x^2} + \frac{\partial U}{\partial z}\frac{\partial^2 z}{\partial x^2} = 0, \\ (26)\quad &\text{b.} \quad \frac{\partial^2 U}{\partial y^2} + \frac{\partial U}{\partial z}\frac{\partial^2 z}{\partial y^2} = 0, \\ &\text{c.} \quad \frac{\partial^2 U}{\partial x \partial y} + \frac{\partial U}{\partial z}\frac{\partial^2 z}{\partial x \partial y} = 0. \end{aligned}$$

By definition

$$r = \frac{\partial^2 z}{\partial x^2}, \quad s = \frac{\partial^2 z}{\partial x \partial y}, \quad t = \frac{\partial^2 z}{\partial y^2}; \text{ and } \frac{\partial U}{\partial z} = g.$$

Hence

$$r - t = \frac{U_\Delta}{g} \tag{27}$$

and

* The method of obtaining these derivatives of $z$ with respect to $x$ and $y$ when $z$ is defined implicitly, as in (21), is fully discussed in Goursat-Hedrick, *Mathematical Analysis*, Vol. 1 (Ginn & Co., 1904), p. 42.

$$s = \frac{-U_{xy}}{g}, \tag{28}$$

where we have used (22), (23), and (24). The first of these is the difference of (26a) and (26b) and the second is equivalent to (26c).

We must express all our results concerning curvature in terms of $U_\Delta$ and $U_{xy}$, which are the quantities observed by the torsion balance. Equation (18) becomes

$$w = \frac{1}{g}\sqrt{U_\Delta^2 + 4U_{xy}^2} \tag{29}$$

and equations (17) and (20):

$$\sin 2\lambda = \frac{\mp 2U_{xy}}{\sqrt{U_\Delta^2 + 4U_{xy}^2}}, \quad \cos 2\lambda = \frac{\pm U_\Delta}{\sqrt{U_\Delta^2 + 4U_{xy}^2}}, \tag{30}$$

and

$$(k_1 - k_2) = \pm \frac{1}{g}\sqrt{U_\Delta^2 + 4U_{xy}^2}, \tag{31}$$

respectively.

If, in (31), we use the positive sign, as is customary, then $k_2$ becomes the curvature which is algebraically less in value than $k_1$, and the value of $\lambda$ corresponding to this least curvature is defined without ambiguity in sign:

$$\sin 2\lambda = \frac{2U_{xy}}{\sqrt{U_\Delta^2 + 4U_{xy}^2}} \tag{32}$$

and

$$\cos 2\lambda = \frac{-U_\Delta}{\sqrt{U_\Delta^2 + 4U_{xy}^2}}. \tag{33}$$

This is the value of $\lambda$ usually used in torsion balance work. Also the value of

$$R = |g(k_1 - k_2)| = \sqrt{U_\Delta^2 + 4U_{xy}^2} \tag{34}$$

leads to

$$R = \frac{-U_\Delta}{\cos 2\lambda}. \tag{35}$$

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1260–1336, 40 FIGS.

# ADVANCES IN TECHNIQUE AND APPLICATION OF RESISTIVITY AND POTENTIAL-DROP-RATIO METHODS IN OIL PROSPECTING[1]

C. A. HEILAND[2]
Golden, Colorado

## ABSTRACT

The successes which have been obtained with electrical methods of prospecting in detecting metallic ore bodies have led to repeated attempts to use them also in oil prospecting, both in structural work and in locating the oil itself. These attempts have not met with as much success as the application of electrical methods to the location of ore bodies; however, the interest in the possibilities of electrical prospecting as applied in oil work has been aroused again of late, due to the perfection of the resistivity and potential-drop-ratio method in regard to the determination of the depth to geologic bodies.

The object of the writer is to give a summary of the whole field of the resistivity methods, with particular reference to the recent developments. The factors affecting the resistivity of rocks, and methods for the determination of resistivities of rocks and formations are described. Then follows a description of the various surface-potential methods. First, the resistivity methods proper are discussed, with reference to electrode arrangement, apparatus, and methods of interpretation used. Second, the potential-drop-ratio methods are treated, also with regard to the electrode arrangements, apparatus, and methods of interpretation. The opinions of various authors are discussed who have expressed their views about the possibilities of locating oil directly by electrical methods, and examples are presented of results which have been obtained thus far with resistivity methods, both in structural prospecting and in attempting to locate the oil directly.

## A. Principles and History of Resistivity Prospecting

In prospecting for oil structure, the four major geophysical methods—gravitational, magnetic, seismic, and electrical—have been widely used. Both the seismic and electrical methods have a distinct advantage over the gravitational and magnetic methods: the possibility of controlling the depth of penetration. This is an important factor in the interpretation of the results, as not only the physical characteristics but also the depths of geologic formations are obtained.

Thus, the seismic and electrical methods as applied in oil prospecting have a number of features in common; on the other hand, they

[1] Read before the Association of the Oklahoma City meeting, March 25, 1932. (Series of publications No. 43, Dept. of Geophysics, Colorado School of Mines.)

[2] Professor of geophysics, Colorado School of Mines.

also differ in a number of respects. The seismic method is essentially a dynamic method (velocity measurements) while the electrical method is essentially a static method (determination of potentials and electromagnetic fields), disregarding for the moment that the element of time enters into the latter through frequency and phase. The seismic and electrical methods each have a dual advantage; namely, that two types of the energy may be observed; in seismic methods, the refracted and reflected energy; in electrical methods, the potential distribution and the electromagnetic field of the ground currents. As far as seismic methods are concerned, the variety of application is very nearly exhausted with the foregoing. In electrical methods, added advantage is obtained by varying the type of application of primary energy: first, in regard to frequency; second, by employing either galvanic or inductive coupling.

Notwithstanding such advantages, electrical methods, as a whole, have not found such wide application in oil work as seismic prospecting. One reason for this is their more complicated field technique when the horizontal radius of operation is increased. Another reason is the limit in depth penetration when the frequency is increased. A third reason is the following: in most geophysical methods, the sought formations must have a thickness comparable with their depth. This holds for the seismic refraction method and the electrical-potential-methods. Noted exceptions are the seismic reflection-method, in which even a comparatively thin formation may still be noticed, provided it has good reflecting characteristics, and the inductive electrical method, in which a thin layer may also be determined, provided it excels in conductivity. However, there again, the electrical methods are at a disadvantage, as the depth penetration, according to practical experience, of the inductive method is not nearly as great as that of the seismic reflection method. A fourth reason, finally, for the more limited application of electrical methods is purely geological; namely, that the factors which can modify the electrical characteristics of formations in both horizontal and vertical direction (such as pore volume and electrolytic conductivity of moisture) are more numerous than similar factors affecting their elastic characteristics. Theoretically, all these obstacles could be amply compensated if it should be possible to perfect electrical methods to such a degree as to enable the direct location of petroleum. However, the reasons that are a great handicap to such effort are again purely geological in nature; namely, the variable factors influencing the electrical characteristics

of formations as already stated are those which in most cases mask the effect of the oil.

On the other hand, it must be admitted that notable advances have been made in approaching the solution of the problem, at least for favorable conditions. Furthermore, remarkable progress has been made in reducing the difficulties which have been outlined in the preceding paragraph; that is, attempts have been made to increase the depth penetration, and to perfect the technique in such a way as to obtain a more interpretable type of indication.

It is quite logical that the resistivity and surface-potential methods offered the greatest possibilities in this respect; for the first necessity in attempting an increase in depth penetration is a decrease in working frequency. For inductive methods, this would materially reduce the current strength induced in subsurface conductors; for electromagnetic methods, it would embody a complication in methods of observation (replacement of the telephone by the galvanometric-rectifier method, or, if the telephone is to be retained, the use of a frequency converter).

From what has gone before it is obvious that an increase in depth penetration should be concomitant, if possible, with a greater precision in determining effects from such depths. Therefore, efforts have been made to find such electrode arrangements which would give the most distinct indication of formation boundaries, as the original Wenner 4-terminal, and similar electrode assemblies do not always give readily interpretable curves. Probably the most successful accomplishment along this line has been the perfection of the potential-drop-ratio method which required an appreciable modification in the technique of the resistivity measurement which had been employed up to that time. The potential-drop-ratio method permits the determination of small differences in apparent resistivity with a great deal of precision, requires no connection of the ratiometer to the power electrodes, and gives well interpretable curves.

There is a great deal of literature on the resistivity method (see reference list at the end of this article), chiefly referring to the application of the method in mining and civil engineering. In the geophysical laboratory of the Colorado School of Mines, extensive studies have been made on the application of resistivity methods, not only to the problems already mentioned, but also to structural oil prospecting. The Gish-Rooney equipment was perfected, model experiments were made, a Racom outfit was acquired through the courtesy of the

Swedish American Prospecting Corporation, and a number of encouraging results were obtained on geologic structure.

The object of the writer is to give a preliminary account of some of the results obtained, and to present a review of the entire field, covering both technique and results obtained by other authors.

As our activities are not limited to research in electrical prospecting alone, the work has been carried through a comparatively great length of time, and various associates of the writer have been engaged in the work. Grateful acknowledgment is made for the contributions of data to T. A. Manhart, C. D. Keen, J. A. Malkovsky, D. H. Griswold, to the Swedish American Prospecting Corporation for part of the equipment, and to Harry Aurand and R. Clare Coffin, of the Midwest Refining Company, for permission to use some of the data and experience which this company has obtained in resistivity work.

As the name indicates, resistivity methods are electrical methods in which the variation of resistivity is measured on the surface. Numerous methods are available for measuring resistivities, either in the well known resistivity bridges for D. C. or A. C., or by the use of ohmmeters, or finally, by separate measurements of voltage drop and current. As for known or constant current, the resistivity follows immediately from the potential distribution, all methods for the determination of potential differences or potential ratios on the surface, the so-called surface-potential methods, may also be included under the heading of resistivity methods.

It is not surprising that attempts were made rather early to use the simple idea of resistivity measurements in prospecting. As early as 1900, Brown and McClatchey applied for a patent on resistivity measurement in this country, and at the same time Daft and Williams, in their English and American patents, suggested the use of potential-difference observations for resistivity work. W. Petersson (ref. list No. $III_1$) describes a qualitative resistivity method for the location of ore, consisting of a buzzer and telephone, the intensity of the sound received being an indication of ground conductivity. The method was used successfully in Sweden in 1906.

The early attempts at the resistivity method were, however, only of a qualitative nature, as neither potential differences for fixed electrode spacings, nor even equipotential lines were observed.

The credit for making the first systematic studies of ground resistivities goes to C. Schlumberger, who began work on the method in

about 1913. The first year in which he applied the method of resistivity mapping was 1920, and numerous structural studies for commercial purposes were carried out by this company in subsequent years.

Schlumberger obtained a French patent on his resistivity method on September 15, 1925.

Considerable interest was attracted at the same time to an identical method, described by Gish and Rooney, December, 1925 (ref. list No. $III_2$), which was used in determining earth resistivities for the study of earth-current and related magnetic phenomena. Their method was based on Wenner's method of measuring earth resistivity, published in 1915 (ref. list No. $II_1$).

The Gish-Rooney method was taken up with considerable interest by a number of mining companies; primarily, the Michigan School of Mines has been largely responsible for the advances of this method in mining. The papers written by W. O. Hotchkiss, J. Fisher, and W. J. Rooney (ref. list No. $III_8$) in 1929, report on the results obtained in the Michigan copper and iron country.

At about the same time, the U. S. Bureau of Mines became interested in resistivity work, and coöperated with A. S. Eve and D. A. Keys in the experimentation with electrical methods. Their studies have continued up to the present time, and the results are recorded in numerous papers, written by F. W. Lee, A. S. Eve, D. A. Keys, and J. H. Swartz (ref. list Nos. $II_3$, $I_6$, $III_{3,4,9,19,29,30,33,37}$).

A number of fundamental papers also appeared on the theoretical foundation of the method, written by J. N. Hummel, W. Weaver, D. O. Ehrenburg, Lancaster-Jones, Tagg, R. J. Watson, T. Roman, L. J. Peters, J. Bardeen, S. Stefanesco, and C. and M. Schlumberger (ref. list, section II).

Meanwhile, in 1928, an important application of the resistivity method had been found, the determination of depth to bedrock in dam sites. Papers by I. B. Crosby and E. G. Leonardon (ref. list No. $III_{6,12,18,20,25,32,35}$) deal with this application.

As far as the use of resistivity methods in oil work is concerned, the Schlumberger Company had proved the practicability of the method in structural studies since 1921. Work was then begun in the Pechelbronn oil region and continued until 1926. In Roumania, commercial work was carried out, among others, for the Steaua Romana in 1923–1926. Salt domes were located in the Alsace region in 1926–1927.

Resistivity prospecting for oil structures was begun in the United

States by 1925, when the Schlumberger Company was engaged to work for the Roxana Petroleum Corporation and the Shell Company of California. The work for the latter continued to about 1929.

A number of oil companies have carried on extensive studies with their own electrical resistivity and potential equipment, such as the Sun Oil Company, the Pure Oil Company, and the Midwest Refining Company.

In addition to the Schlumberger Company, several other geophysical prospecting companies have since taken up studies, such as the McCollum Exploration Company, the Swedish-American Prospecting Corporation, the Radiore Company, the Elbof Company, the Geophysical Service Inc., and the International Geophysics, Inc. Very little has been published on the successes of structural resistivity prospecting; practically everything is by members of the Schlumberger Company (ref. list No. $III_{7,10,12,16,18,20}$).

One of the outstanding developments in resistivity-prospecting methods in late years was the perfection of the potential-drop-ratio method. This was suggested by three authors at almost the same time. Although a 3-contact ratio arm bridge was devised by A. B. Edge as early as 1925 and was used in northern Rhodesia during that year, and although an A. C. potential ratiometer was used, up to the end of 1929, by the I.G.E.S. in Australia, it was not until January, 1931, that the method was first described by Edge (ref. list No. $IV_4$). Already before this publication appeared, Koenigsberger (ref. list No. $IV_1$) had suggested a potential-ratio method in 1930. Two months after Edge's article had been published, H. Lundberg and Th. Zuschlag published their description of the Racom (ref. list No. $IV_5$).

The potential-drop-ratio method, on account of its sensitivity and accuracy, gives very good results when suitable instruments are used, and it is believed that it is only in its initial stage of development.

There follows now a discussion of (1) the resistivity of formations and methods for its determination; (2) a description of the technique of resistivity and potential-drop-ratio methods; and (3) a discussion of the results obtained in structural work.

### B. Resistivity of Formations and Rocks

With the exception of the few rocks which contain some sort of a metallic mineralization (mostly sulphidic), and the conductivity of

which is, therefore, of a metallic nature, the conductivity of all the other rocks and formations is of a purely electrolytic character. Therefore, all these rocks are highly resistant when dry; or, in other words, the conductivity of a rock is proportional to the amount of water which it contains, and to the quantities of ionized salts dissolved in the water.

### I. FACTORS AFFECTING ROCK RESISTIVITY

From what has been previously stated, it is obvious that the resistivity of the formations which are of importance in electrical prospecting is affected primarily by the following factors: (1) the resistivity of the mineral constituents; (2) the resistivity of the water filling the pores; (3) the pore volume; (4) the shape of the pores; (5) the temperature; and (6) the pressure at the particular depth of the formation under investigation.

As far as the resistivity of the mineral constituents is concerned, which make up most of the rocks encountered in oil resistivity prospecting, this factor is of comparatively small influence. As has been stated before, only rocks with a metallic mineralization have a comparatively low resistivity, while the resistivity of the mineral matter in most barren sedimentary and igneous rocks is so high (of the order of $10^6$–$10^{14}$ ohms cm.$^{-3}$), that they may be considered as insulators for the purposes of geophysical prospecting; that is to say, in most sedimentary rocks, the influence of the pore volume and of the conductivity of the waters filling the pores is so much more predominant a factor in determining the conductivity of the rock, that the influence of the resistivity of the mineral matter may be disregarded in comparison.

The resistivity of the water filling the pores in such rocks as are of importance in resistivity oil prospecting is of paramount importance.

Following Sundberg (ref. list No. $I_{9,10}$), the impregnating waters may be divided into the following groups.

*A*. *Surface waters* (waters from the surface of the ground down to and including the ground water).

(a) Fresh water, such as rain, snow, lake, river, and ground water, and the normal moisture in the upper soil. The percentage of dissolved substances ranges from 0.01 to 0.1 at an average. These dissolved substances are ordinarily carbonates and silicates and small amounts of chlorides and nitrates of calcium, magnesium, sodium, and potassium. The resistivity of such surface waters varies at an average between 30,000 and several hundred thousand ohms cm$^{-3}$.

(b) Mineral waters with varying concentrations. Such waters are ordinarily locally limited, and are not commonly encountered on the surface of oil-bearing structures; they are not of as great importance for our problem as those previously mentioned, and the deep waters to be discussed now.

*B. Deep waters.*

(a) Connate waters.
These waters are ordinarily encountered in oil fields. As the name indicates, their origin dates back to the time when the formations were laid down in sedimentary basins. They contain chlorides of sodium, potassium, magnesium, and calcium. They differ from sea water, however, by the abundance of calcium chloride and by the absence of sulphates. They are distinguished by a very wide range of concentrations, from dilute to concentrated solutions. Consequently, their resistance also varies within wide limits, to as low as a few ohms $cm^{-3}$.

(b) Mine waters.
These waters are ordinarily solutions of metal sulphates, but they also contain carbonates of sodium, calcium, and magnesium. They vary widely in resistivity which may be as low as 30 ohms $cm^{-3}$.

The most important chemical constituent of waters of all kinds which determines their conductivity is the chlorine content. Figure 1 *b* illustrates the relation between resistivity and chlorine content for three ranges of concentration.

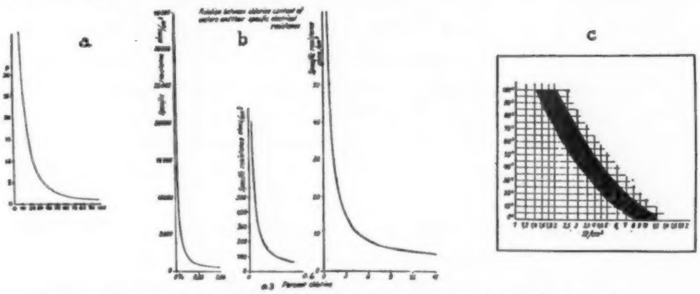



FIG. 1.—Factors controlling resistivity of rock waters (after Sundberg).
*a:* Relation between resistance factor $P=\rho_x/\rho$ and percentual volume $v$ of water in rocks. ($\rho_x$=resistivity considering grain arrangement; $\rho$=resistivity not considering grain arrangement.)
*b:* Relation between chlorine content of waters and their specific electric resistance.
*c:* Relation between temperature and specific electric resistance for electrolytes.

The next outstanding factor determining the resistivity of rocks and formations is the pore volume. The pore volume depends on the size and shape of the grains, and their mutual arrangement. The

porosities of such formations as are ordinarily encountered in oil prospecting cover a wide range, approximately between 10 and 45 per cent.

The pore volume, of course, is equal to the maximum amount of water which is possible in a rock. This condition is generally assumed to exist below the ground-water level, except where the water has been replaced by gas or oil. Above the ground-water level, there are considerable variations, which account for the varying values of resistivities that are often encountered near the surface in resistivity work. The moisture content of the soil is generally very low near the surface on account of evaporation, then increases rapidly with depth, then decreases and reaches a maximum in the ground-water level.[1] At the immediate surface, the moisture, and therefore the resistivity, varies considerably with the meterological factors. During rainfalls, the resistivity will usually be very great on account of the purity of waters; during droughts, highly conductive waters migrate upward, resulting in a decrease of the resistivity of the formations concerned.

Due to the fact that the conductive medium, the water, in a rock is not everywhere of the same section, but varies from a very thin section where the grains are touching each other to a greater section where grains are not in contact, the relation between pore volume and rock resistivity is not altogether simple; it may, however, be worked out for certain simplified assumptions; for instance, for the case that the grains are spheres of equal size or for the case that the pores have the shape of three mutually perpendicular and parallel systems of tubes. Figure 1 *a* shows the relation between a resistance factor $P$, which is the ratio of the actual water resistivity depending on porosity to the water resistivity, without regard to porosity (Chapter B, II, d), and the water volume of a rock in percentage.

Finally, the temperature and the pressure influence the electrolytic resistivity of rocks. Figure 1 *c* shows the influence of temperature; an increase in temperature decreases the resistivity considerably; the relation shown in the figure holds for any kind of an electrolyte, and indicates that a rise in temperature by only 25° C. from zero is sufficient to increase the conductivity of a rock approximately 100 per cent.

The effect of pressure is much smaller and is illustrated in Figure 2. The effect is different on concentrated solutions from what it is on solutions of smaller concentrations. At any rate, with the maximum

[1] For details, see ref. list III, 38.

effect on a concentrated solution, a pressure corresponding with a depth of burial of nearly 10 kilometers would bring about a change in resistivity of only 10 per cent.

More details on the effect of water on rock resistivities may be obtained from K. Sundberg's papers (ref. list $I_{9,10}$).

### II. DETERMINATION OF RESISTIVITIES

The experimental determination of the resistivity of rocks or formations is by no means a very easy matter. This is chiefly due to the

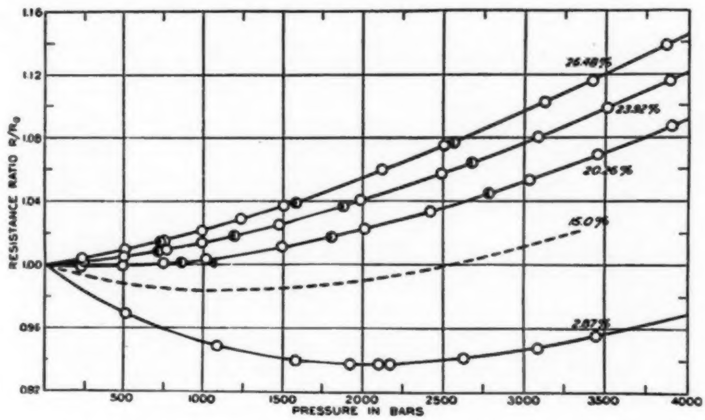



FIG. 2.—Relation between pressure and resistivity of electrolytes (after L. H. Adams and R. E. Hall).

fact that a sample can not well be kept in the same condition after being removed from its location as it has been in before it was disturbed, chiefly in reference to its mechanical constitution and its moisture content. Therefore, experiments to test the resistivity of rocks are usually made, whenever possible, on outcrops, or by means of special equipment, in wells (Schlumberger method). If there is no possibility of avoiding the testing of samples, the tests should be made in a portable apparatus immediately after the sample has been taken, or else, the resistivity of a formation may finally be computed from the pore volume of the constituent rock and the conductivity of the impregnating water (Sundberg method).

#### a. DETERMINATION OF RESISTIVITIES ON SAMPLES

A simple arrangement for the determination of resistivities of solid rock specimens is shown on the right side of the panel illustrated in Figure 3.

The arrangement consists of a frame supported on springs; one round electrode is connected to the bottom of this frame, the other is attached to the bottom of a spindle. The sample to be tested is placed between the electrode on the spindle and that on the frame, with some tin foil between sample and electrodes. Mercury electrodes may be used on drill core samples instead of the solid metal plates. This arrangement may be placed in a Wheatstone bridge.

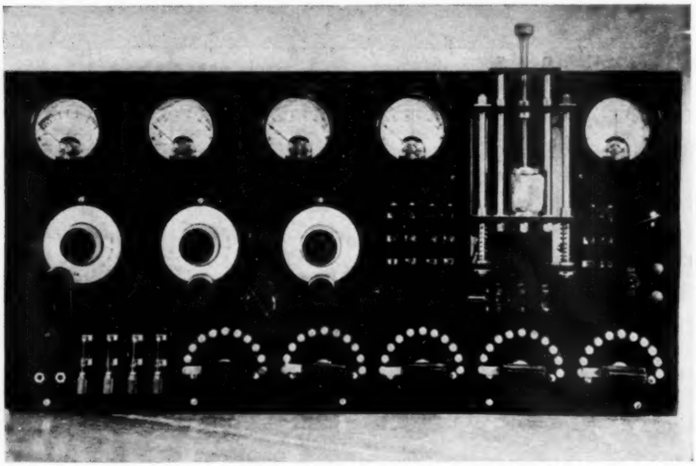


FIG. 3.—A.C. and D.C. resistivity bridge (C S M).

The samples should, preferably, have a simple geometric shape. If $l$ is the length, $s$ the section of the sample, $R$ the observed resistance and $\rho$ the resistivity to be determined, $\rho = \frac{R \cdot S}{l}$.

The resistivity is usually expressed in ohm·cm (see ref. list I, 12). In some publications ohm·meters are used; resistivities expressed in the latter units are one hundredth as large as resistivities expressed in the former units.

The bridge shown in Figure 3 has on the left side the controls for

high frequency tests, and on the right are the meters and switches for D.C. testing. The bridge is A.C. operated, and consists of an oscillator, the frequency of which may be varied within wide limits in the high frequency range. A pickup coil with variable coupling transfers the energy of the oscillator to the testing circuit, which is essentially an A.C. Wheatstone bridge. Non-inductive resistors are used; the switches for the 10, 100, 1,000, 10,000 and 100,000 ohm ranges are seen on the panel. The same resistors are used when the bridge is operated on D.C. The binding posts on the extreme right edge of the panel are for making connections to the testing battery or a low frequency oscillator or commutator.[1]

The bridge is only for small samples of regular shape, such as diamond drill cores and the like. For larger specimens of consolidated rocks, we use a different bridge which consists of a frame with two spindles to hold the specimen, and four arms spaced at equal intervals which carry contact points at their end. The Gish-Rooney (or Wenner) method is applied in testing the specimen, and the Gish-Rooney equipment as used in the field can be connected directly to this bridge.

M. W. Pullen (ref. list No. $I_6$) uses also direct and alternating current in his resistivity tester. The resistivities are measured by comparing the resistance of the specimen with a known resistance, that is, by switching the current from one circuit containing this specimen over to the other circuit containing the known resistance. The electrodes used were chiefly mercury pools, held in place upon the specimen by wax dams if the specimen had an irregular shape, or by a bakelite cup and a paper collar for drill cores. To eliminate surface leakage of current across the specimen, guard rings were applied. In using continuous current, the observed resistivity values were found to change with time on account of the variable polarization. Therefore, discontinuous current was found to be more satisfactory, which was obtained by shortening the regular 60-cycle A.C. from a light circuit through a potentiometer (for obtaining different test voltages) and using a copper oxide rectifier to make the use of a direct current galvanometer possible (Fig. 4 *a*).

For large specimens of irregular shape, not only the Gish-Rooney four-electrode method may be used, but also two like electrodes of regular geometric shape may be employed, provided their distance is small as compared with the dimensions of the sample. The theory

[1] This resistivity bridge was developed largely after the bridge used by the Radiore Company.

of such an arrangement (Sundberg, ref. list No. I₉) shows that for square electrodes with sides of 0.37 cm. the measured resistance is equal to the specific resistance of the specimen.

The bridges described before may only be used for solid specimens. They are not applicable for soils. For testing of soil samples in

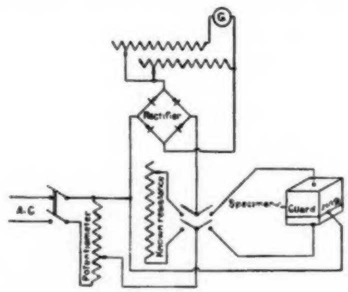



FIG. 4a.—Circuit of A.C. rock-resistivity tester, operated from light socket (after M. W. Pullen).

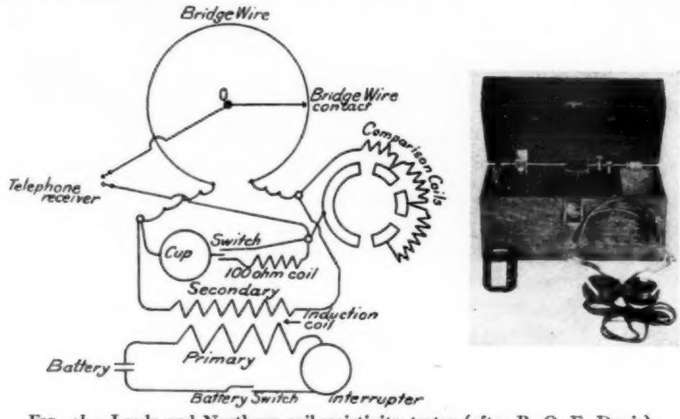



FIG. 4b.—Leeds and Northrup soil-resistivity tester (after R. O. E. Davis).

the field, the Leeds and Northrup soil bridge may be applied. The instrument (known as the Wheatstone-Kirchhoff bridge) as shown in Figure 4 *b*, is a modified form of a Wheatstone bridge. As a source of energy, a buzzer operated by a dry cell is used; consequently, a telephone may be employed to indicate the balance. The soil to be tested is placed in a cup; this represents the variable resistance in one arm

of the bridge; the fixed comparison coils are in the other arm of the bridge; both connect to the variable slide wire and the secondary of the buzzer coil. The comparison coils are made up of three fixed resistances of 10, 100, and 1,000 ohms. An additional resistance of 100 ohms may be used in series with the cup when its resistance is low. The balance is adjusted on the slide wire, with proper setting of the fixed resistances, and the reading on the slide wire is multiplied by the resistance of the comparison coil used.

The use of the cup is very convenient as not only soils, but also electrolytic solutions may be tested in it. It may be standardized by using solutions of known concentrations. The results must be re-

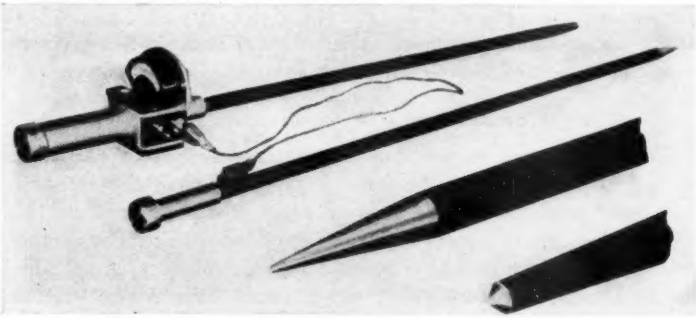


FIG. 5.—Shepard earth-resistivity meter.

ferred to a normal temperature. The publication by R. O. E. Davis (ref. list No. $I_1$) gives a number of tables on resistivities of soils and solutions which will be found valuable when using this bridge.

*b.* DETERMINATION OF RESISTIVITIES ON OUTCROPS

On account of the difficulties which are inherent in the accurate determination of the resistivity of samples and which have been discussed before, determinations of the resistivities on outcrops, or, generally speaking, on the ground surface are ordinarily much more satisfactory.

Quite a few methods may be used for this purpose. For approximate tests, the Shepard earth-resistivity meter may be employed (Fig. 5). It is an instrument working on D.C.; the ohmmeter and the battery are mounted on one probe; the probes are made of iron, and

the cathode is larger than the anode, reducing polarization to a great extent. For this purpose, the electrodes have a large ratio of areas, as seen in the figure.[1]

For more accurate work on the surface, the Megger and McCollum's earth-resistivity testers, or the 4-terminal Gish-Rooney equipment is used, which will be described later.

J. Koenigsberger (ref. list No. $I_5$) uses two circular iron electrodes about 25 cm. in diameter, and about 5 mm. in thickness, provided with a contact substance which is either hematite powder or a clayey paste with an aqueous solution of $FeCl_3$, or $FeSO_4$, or of 10 per cent $NaCl$. Where the necessity arises of using larger electrodes, iron screens may be employed. As a source of energy, a buzzer is used at a frequency from 100–400 cycles; the electrodes are placed in a Wheatstone bridge with a telephone as indicator. Koenigsberger gives the formulae to be used with this arrangement of the electrodes.

### c. DETERMINATION OF RESISTIVITY IN WELLS

This is the only method for obtaining accurate resistivity values for any formation below the surface. The equipment and technique has been perfected by the Schlumberger Company (ref. list No. $I_{8,11}$), and excellent results have been obtained with it. The arrangement is shown in Figure 6. It consists of four electrodes, two of which are supplied with current, while the potential difference between the two intermediate electrodes is observed; one current electrode is grounded at the surface. The arrangement of the three other electrodes always remains fixed at any depth. With the symbols used in the figure, the resistivity at any depth is given by the relation

$$\rho = \frac{4\pi\Delta V}{i}\cdot\frac{rr'}{r' - r}$$

if $i$ is the current read on a milliammeter in the current circuit and $\Delta V$ is the potential difference read on a potentiometer between the electrodes 2 and 3. Excellent results have been obtained by this method, and have occasionally resulted in the detection of oil and coal horizons which had been overlooked in drilling. The results, together with some outstanding examples, will be discussed later.

[1] *See:* S. Ewing: "Soil Survey Methods," *Oil and Gas Journal*, April 21, 1932, p. 42. C. R. Weidner and L. E. Davis: "Relation of Pipe Line Currents and Soil Resistivity to Corrosion," *The Oil Weekly*, December 4, 1931, p. 26.

### *d*. DETERMINATION OF RESISTIVITIES FROM WATER ANALYSES AND POROSITY DETERMINATIONS

If it is not possible to determine underground resistivities by the Schlumberger method, that is, if there is casing in the well at the depth to be investigated, or if the wells are dry, sufficiently accurate estimates of resistivities of formations may often be obtained by a method suggested by Lundberg (reference list No. $I_{9,10}$), provided water analyses are available for the formations under investigation, which is often the case. If the water analyses can, in addition, be supplemented by a determination of the pore volume of the forma-

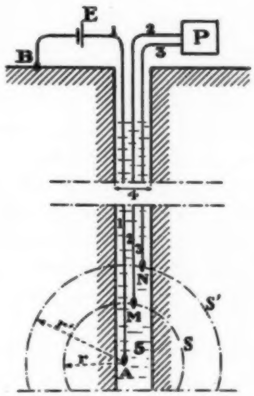



FIG. 6.—Schlumberger's method of measuring resistivities in wells (after C. and M. Schlumberger).

tion from an investigation of drill cores, for instance, a fairly accurate determination of the resistivity of the formation can be made.

If the porosity of a sample is known, the resistance factor $P$ may be found from the diagram in Figure 1 *a*, if it is assumed that all the pores are filled with water; this is ordinarily true, as already stated, below the ground-water level. If the chemical composition of the waters at a certain depth is known, and if it is assumed, with sufficient accuracy, that only sodium chloride is in solution, the diagrams in Figure 1 *b* may be used to determine the resistivity of the water; to convert the results into actual resistivities at a certain depth, the temperature correction illustrated in Figure 1 *c* may be applied.

The resistivity factor $P$ is of the order of 50 to 100 for dense lime-

stones and sandstone, 20 to 40 for clays and sands, and 2 to 20 for porous sands, clays, and soils.

## C. Resistivity Methods

In the two sections that follow, the principles, apparatus, and electrode arrangements used in the resistivity and potential-drop-ratio measurements are discussed first. After that, some outstanding results are described which have been obtained with both methods on geologic structure of various types, as well as in direct prospecting for oil.

Though the purposes for which the resistivity and potential-drop-ratio methods are used are usually identical, these two methods differ essentially in electrode arrangement and technique of measurement.

In the resistivity methods proper, current is usually supplied to two points, and the potential distribution between these two points is investigated by either one or two electrodes. The current is determined which flows between the two outside current terminals, and the potential difference is observed which exists either between the two potential electrodes, or between the one potential electrode and one neighboring current electrode. The ratio of voltage and current, multiplied by a constant depending on the mutual arrangement of the electrodes, gives the resistivity of the surface formation, if only one formation exists within the reach of the whole contacting arrangement. If more formations are present the "apparent" resistivity is measured as a function of the electrode spacing, and thus, as a function of the depth to the interfaces of the formations involved.

In the potential-drop-ratio methods, current is again supplied to two points in the area under investigation; but this time, the investigation of the potential distribution takes place outside of the pole doublet and is usually made in the vicinity of one electrode. The drop of the potential in the vicinity of this one electrode is intimately related to the existence of resistivity changes with depth. Experience has shown that the most interpretable results are obtained by not investigating the drop of the potential itself, but by determining the ratio of potential drops in two adjacent intervals. That is to say, the testing device in this method requires only 3 electrodes, and is independent of any connection to the current circuit or to the source of energy, which gives these methods a distinct advantage over the resistivity methods proper.

We shall first discuss briefly the electrode arrangements and apparatus used in the resistivity methods proper.

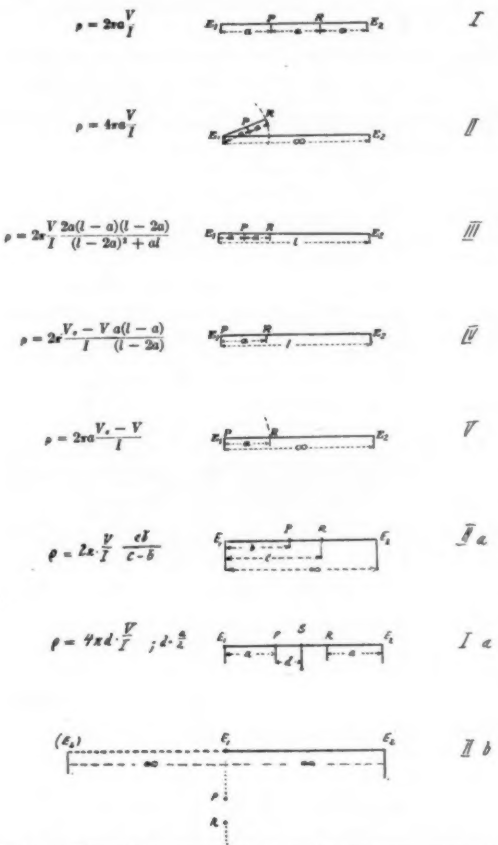


FIG. 7.—Electrode arrangements in resistivity prospecting.

### I. ELECTRODE ARRANGEMENTS

#### *a.* POSSIBLE ARRANGEMENTS

Five possible electrode arrangements which can be used in resistivity work are described in detail, and formulae are given for each arrangement, in J. N. Hummel's publication (reference list No. $II_{12}$) and Figure 7. They are summarized briefly as follows.

(1) Wenner's arrangement, also called simply the 4-terminal method. (This is the electrode arrangement most widely used.) The potential electrodes are arranged in line with the current electrodes, and the spacing of all 4 electrodes is equal. That is, the distance between the outside terminals is $3a$ if $a$ is the electrode interval.

(2) Single-current-probe method: One current electrode is far apart from the other, and the two potential electrodes are used in the vicinity of one electrode. If their interval is $a$, they are so used in the vicinity of the current electrode that the distance of the current electrode from the potential electrode next to it is also always kept equal to $a$. The potential electrodes need not be in a straight line with the current electrodes.

(3) This third possible electrode arrangement is practically identical with that described in No. 2, except that the second current electrode is no longer in infinity, and that the potential electrodes are now in a straight line with the current electrodes.

(4) The fourth method may be called the single-potential-probe method. Again two current electrodes are used, but only one potential electrode, the position of which is varied between the two current electrodes.

(5) The fifth method is identical with the fourth, but this time one current electrode is at infinity. This method may thus be called the single-current and the potential-electrode method.

Two more methods are possible and have been used, both being modifications of the second and the first method already described.

The first of these is the single-probe method by Eve and Keys and is similar to the second method (Fig. 7, *II a*), with the exception that the interval between the two potential and one current electrode is no longer equal; only the spacing between the potential electrodes remains constant.

The second of these additional methods is a modification of Wenner's and Gish-Rooney's 4-terminal method. An additional electrode is provided between the potential electrodes; measurements take place as before, that is on four electrodes. Two sets of results, however, are now obtained: one (at the right), using the electrodes $R$ and $S$; the second (at the left), using the electrodes $P$ and $S$. This is called Lee's method (see ref. list No. III, 37) of partitioning.[1]

[1] A third additional method may be mentioned here, which is the "Potential center displacement" method of S. H. Williston and C. R. Nichols, described by F. H. Lahee in the third (1931) edition of his *Field Geology* (p. 694). The electrode arrangement is that shown in IV in Figure 7. The object of the method is the measurement of the displacement of the potential center from its geographic center between the two primary electrodes which it would occupy in homogeneous ground. In surveying an area, the whole contacting arrangement is stepped forward as in resistivity mapping, the electrode base remaining constant. The depth of penetration is roughly equal to half the length of this base; an area may be covered with different exploration depths as in resistivity mapping. The potential center displacements are at a maximum over the lateral edges of resistant bodies; zero displacements between two opposite maxima would thus indicate the crest of an anticline, etc.

In Figure 7, these electrode arrangements are shown. Also the formulae are given for the computation of the resistivities of the ground if no unhomogeneity is within the reach of the measuring arrangement. Otherwise, the resistivity values obtained by the application of the formulae represent apparent resistivities only, from which the true resistivities, as well as the depth to the formation boundaries, may be obtained by applying methods to be described later.

### *b.* CUSTOMARY ELECTRODE ARRANGEMENTS

Of the many electrode arrangements previously described, only a few are customarily applied and it all depends on the purpose for which a resistivity investigation is made, which method is used.

There are two distinct applications of the resistivity method. First is the method of resistivity mapping. The object of this method is to obtain a contour map of the area, showing lines of equal resistivity. These lines represent the ground resistivity only to a definite depth, and, to facilitate the interpretation of the results, two or more contour maps may be made for the same area, representing the resistivity down to two depths of investigation. This can be accomplished simply by working with two fixed electrode separations, as described hereafter. The second method is the so-called method of electrical drilling. The results are to give the vertical variation of the resistivity at one point only and the depth at which any changes occur. The only way to accomplish this is, of course, to survey along a line beginning at the point where the vertical resistivity variation is to be tested; and this line is the longer, the greater the desired depth penetration. It is thus seen that accurate results in this method depend altogether on the question whether or not the vertical differentiation of the resistivity carries unchanged in a horizontal direction below the last point of measurement.

#### *b* 1. RESISTIVITY MAPPING

In this method, usually the 4-terminal electrode arrangement is employed and the whole contacting outfit is carried over the area to be surveyed with a constant electrode separation.[1] If it is desired to obtain two equi-resistivity maps covering two depths of penetration, two electrode separations are used at each point of observation. The results of some equi-resistivity surveys are shown in Figures 26, 28, 29, 30.

[1] As a matter of interest it may be mentioned that the equiresistivity method has recently been used for oil prospecting in shallow water (ref. list No. III, 41).

### b 2. VERTICAL ELECTRICAL DRILLING

For this purpose, several methods of those already enumerated may be used.

(1) The method that has been most commonly used is probably the 4-terminal Gish-Rooney-Wenner method (Fig. 7 *I*). The electrodes are arranged always symmetrically around the point to be drilled electrically; that is to say, this point is located where the electrode *S* in the Lee partitioning method would be placed. By applying this modification of the Gish-Rooney method, one readily obtains the distribution of resistivity at the north and at the south (or any other two opposite directions) from the midpoint; that is to say, it is possible to determine by this method if there is a dip of the formations, or if formations come in north of this point that may be absent in the south.

(2) The method that has been used perhaps as frequently as the 4-terminal method for electrical vertical drilling is the single-current-probe method, that is, the investigation of the potential distribution in the vicinity of one current electrode only. For this purpose, either the electrode arrangement shown in *II* in Figure 7 may be used ($ER$ equal to $2a$) or the modification shown in *IIa*. As indicated in Figure 7 *II*, it is not necessary that the two potential electrodes be in line with the current electrodes; in fact, to eliminate completely the influence of the second current electrode, which is assumed to be at infinity, the line of measuring the potential should be located on a circle through $E_1$ with the distance $E_1E_2$ as radius around $E_2$; or, if that is not feasible, a close enough approximation may be obtained by running the potential measurements on a line at right angles to $E_1E_2$. This is the method employed by Ehrenburg and Watson (with $EP=a$, $ER=2a$) (reference list No. $\mathrm{II}_{11}$). Gilchrist has applied (reference list No. $\mathrm{III}_{34}$) a modification of this last method by using two electrodes $E_2$ at either side of $E_1$, and passing currents of equal strength through both circuits (Fig. 7 *II b*). Instead of using only one current base $E_2E_2$ at right angles to the potential line, any number of current bases, arranged in the form of a symmetrical star, may be employed.

## II. APPARATUS FOR RESISTIVITY WORK

We now come to a description of the equipment used in resistivity work. In order not to make this paper unduly long, rather extensive use of figures will be made instead of giving lengthy descriptions of the apparatus. Further details may be obtained from the literature given in the reference list.

*a*. GENERAL: POWER SOURCES

As a source of power, one Radio B battery, or two, may be sufficient, depending on the length of the current basis, of course. If very great depth penetration is required, a D.C. generator is used, driven by a gasoline engine. When using a Megger, a hand-driven D.C. generator is used, which is incorporated in the meter box. Due to the fact that polarization must be eliminated, if non-polarized electrodes are not used, a commutator is provided in the measuring circuit, which brings it about that in reality the current used is not strictly

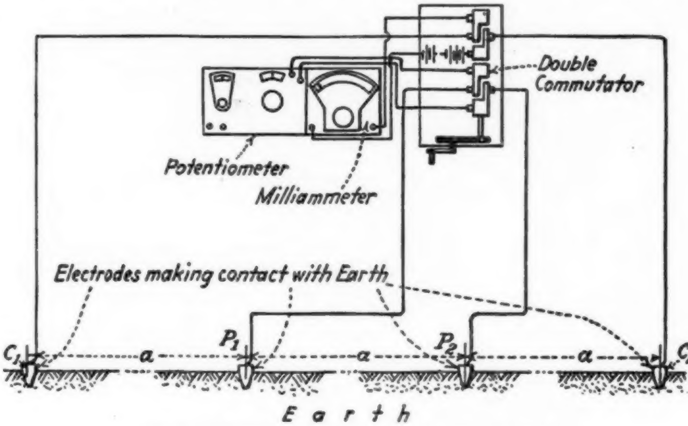



FIG. 8.—Schematic diagram of Gish-Rooney circuit.

D.C., but an alternating current of low frequency. Induction effects are, therefore, sometimes observed between the current and the potential leads; besides, not the ohmic resistance of the ground is obtained, but the impedance for the particular frequency employed, which for the commutators in Gish-Rooney outfits is approximately 16, and nearly 50 in Meggers.

The only way to avoid polarization and induction effects is by using non-polarized electrodes, which consist of cups filled with copper sulphate and provided with a permeable bottom, made either of porous clay or of wood.

The induction between leads is minimized when using the potential measuring line at right angles to the current basis, as already described.

There is no reason why alternating current could not be used in resistivity work, the same as it is done in the potential-drop-ratio method. For instance, the current base could be supplied with A.C. of moderate frequency by a buzzer, or vacuum-tube oscillator, or by

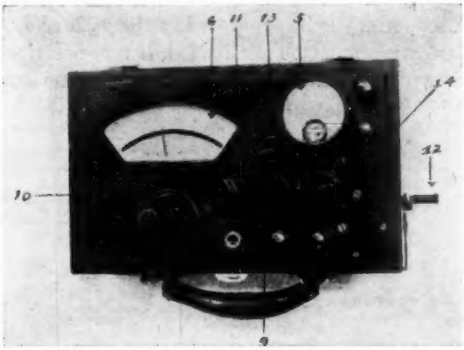
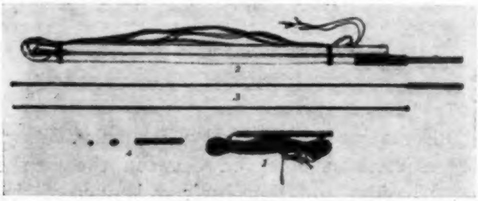


FIG. 9.—McCollum earth-current meter (after McCollum).

EARTH-CURRENT METER

5, milliammeter; 6, voltmeter; 9, commutator switch; 10, short-circuiting switch; 11, voltmeter switch; 12, commutator crank; 13, ammeter switch; 14, resistance switch.



EARTH-CURRENT METER CONTACTORS

1, trench contactor; 2, cantilever contactor; 3, single terminal electrode with extension rod; 4, single terminal electrode (disassembled).

taking, if available, current from the light circuit, and feeding it to the ground through a transformer. The only difficulty would be to obtain an accurate reading of the current; however, the absolute value of the current is not of great importance when using the methods *II*, *II a*, or *II b*. To measure the potential difference between the potential electrodes, it would be feasible to have a compensator, and a lead to

a pickup coil coupled to the generator or the power leads; the object of this lead being to carry the reference e.m.f. and the generator phase to the point of observation.

#### *b.* ORIGINAL GISH-ROONEY APPARATUS

This apparatus has been described so often in the literature that it is hardly necessary to go into more details. It contains a potentiometer for measuring the potential difference between the two potential electrodes, a milliammeter for measuring the current, and a double

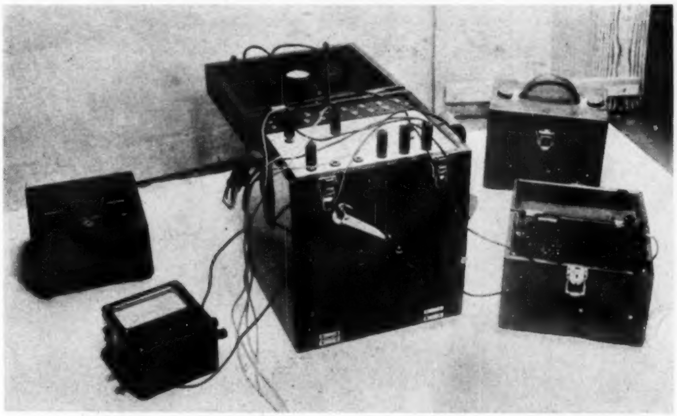


FIG. 10*a*.—First model of CSM Gish-Rooney outfit, built after MSM model. Hand-cranked commutator box which contains also batteries, shown in center; milliammeter at left and potentiometer at right.

commutator, the purpose of which is to pass current to the ground in alternating direction, yet pass the current and the potential to be measured always in the same direction through the meters. Figure 8 shows a sectional view of the apparatus.

#### *c.* MC COLLUM EARTH-CURRENT METER

Although this instrument was developed altogether independently from the Gish-Rooney apparatus and for a different purpose, it is, nevertheless, of practically the same construction as the Gish-Rooney apparatus. It is shown in Figure 9. It has a voltmeter and milliammeter like the Gish-Rooney apparatus, and also a commutator. It differs somewhat from the Gish-Rooney as a number of ranges are

provided for both the milliammeter and the voltmeter, and as non-polarized electrodes are provided (reference list No. $I_2$).

### *d.* MODIFIED GISH-ROONEY APPARATUS

A number of oil and mining companies have designed their own Gish-Rooney equipment, which differs slightly from the original in one way or another. The Michigan School of Mines has obtained much experience in the design of this equipment, and their apparatus

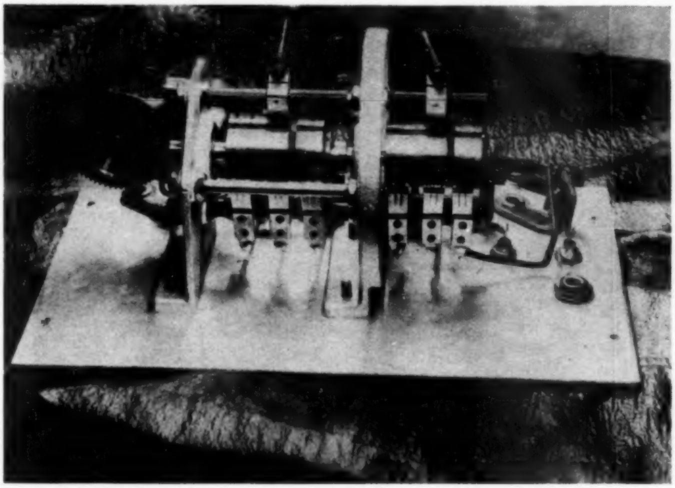


FIG. 10*b*.—Construction of commutator in instrument shown in Figure 10*a*.

was used as model for one of the instruments built in the instrument shop of the Colorado School of Mines (Fig. 10 *a* and Fig. 10 *b*).

Figure 11 shows the latest form of a Gish-Rooney equipment built at the Colorado School of Mines. On the left side of the figure, a box is shown containing the potentiometer, milliammeter, switches and jacks, and below the panel, the commutator, which is driven by a small D.C. motor, operated from a storage battery. The battery box is seen between the reels and the meter box.

### *e.* MEGOHMERS

These instruments have been used for years for the testing of grounds and insulation in electrical power-plant-, railway-, and radio-

engineering. They differ from the Gish-Rooney equipment chiefly in that the potentiometer and the milliammeter are combined in one

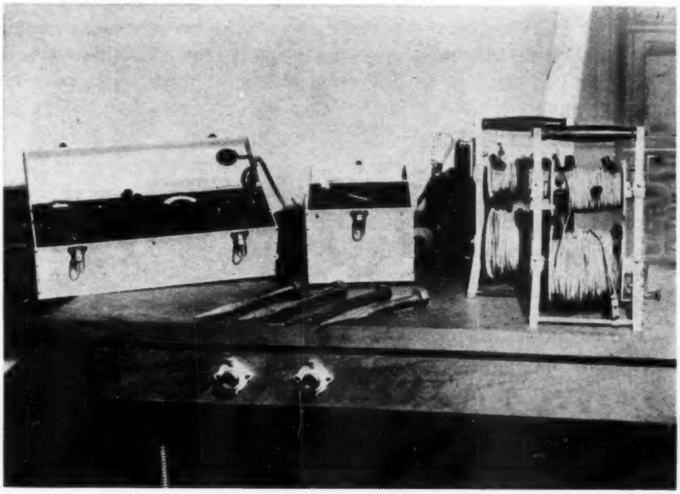


FIG. 11.—Latest CSM model of Gish-Rooney equipment with motor-driven commutator.

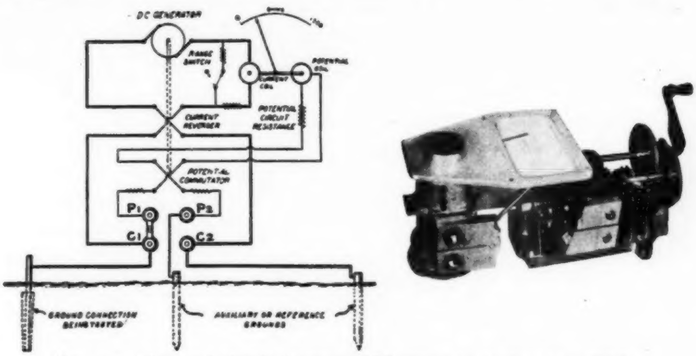



FIG. 12.—View and circuit diagram of Megger manufactured by Biddle.

instrument, the ohmmeter, the moving coil of which has two windings, the voltage and the current winding. They also differ from the Gish-Rooney equipment as the power is not taken from batteries,

but from a hand-driven D.C. generator, on the shaft of which a double commutator, similar to the one used in the Gish-Rooney apparatus, is mounted.

The most important manufacturers of Megohmers or Meggers are: Evershed and Vignoles, Acton, England; James G. Biddle, Philadelphia; and Herman H. Sticht and Company, New York.

The accompanying figures show a number of Meggers, which are all very similar in principle. Details on the construction of these instruments may be obtained by writing to the manufacturers and asking for their catalogs. Figure 12 shows wiring diagram and sectional view of a Megger manufactured by Biddle, and Figures 13 *a* and 13 *b* show Meggers manufactured by the Sticht Company.

### III. INTERPRETATION OF RESULTS

The fundamental principle underlying the interpretation of the resistivity results is comparatively simple.

*The depth reached depends on the spacing of the potential electrodes* (or their distance from a current electrode in methods where stationary current electrodes are used).

In other words, if the observed resistivity values are plotted as a function of the electrode separation (in the 4-terminal method), or as a function of the distance of the potential electrodes from the near current electrode in single-probe methods, then the *electrode separation* or electrode distance *at which* marked *changes in apparent resistivities occur* is *approximately equal to the depth* to the resistivity discontinuities underground.

This statement is made merely to illustrate the nature of the fundamental principle underlying resistivity measurements. In practice, however, there are more difficulties, as the presence of more than one discontinuity of resistivity is considerably complicating.

Actual experience shows that this simple depth rule works surprisingly well in mining when insulated bodies of good conductivity are encountered. In application to stratified ground, severe complications arise, chiefly with the Gish-Rooney method, and particularly, when there is more than one layer present.

In the practice of resistivity work, therefore, we use several lines of attack in the interpretation of results. As in other types of geophysical work, both qualitative and quantitative methods may be applied. The qualitative method usually precedes the quantitative method in application, and the quantitative method is applied if the

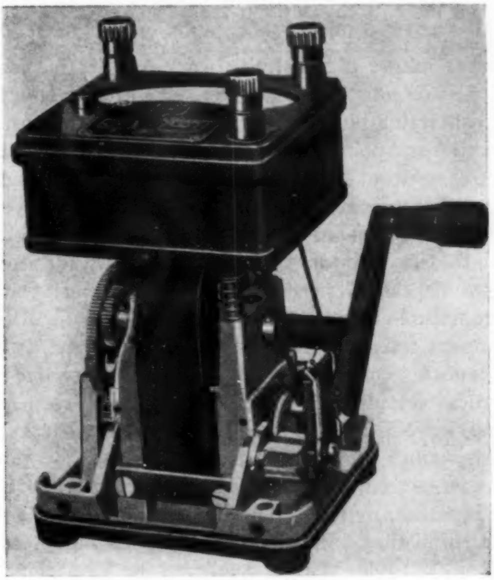


FIG. 13a.—Model D M Megohmer, manufactured by Sticht.

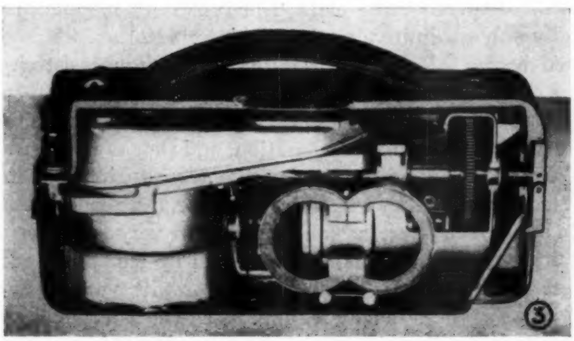


FIG. 13b.—Paragon Megohmer, manufactured by Sticht.

nature of the indications, derived from their qualitative analysis warrants it.

Due to the nature of resistivity work, qualitative methods are usually applied in resistivity mapping. The area is covered with a 4-terminal contacting outfit, and resistivities are measured; the results are plotted and points of equal resistivity are connected by lines which resemble contour lines, and which are interpreted accordingly. The interpretation assumes a somewhat more quantitative nature if, at every point, instead of one electrode spacing, two electrode spacings are used, so that two contour maps may be drawn for any one area, covering two depths of penetration. Finally, considerations of a quantitative nature enter also when the contact plane of two formations of different resistivities is considered, and if one, two, or three of the contacts are in one, and the remainder in the second formation. The theoretical computations for this case have been carried out by Tagg (ref. list No. $II_{10}$) and Hedstrom (ref. list No. $IV_7$) and the results are shown in Figure 14. The curves illustrate how the apparent resistivity is influenced, for various values of resistivity ratios of the formations involved, by the distance of the center of the contacting arrangement from the boundary. The curves of Figure 14 are computed for four electrodes at right angles to the formation boundary, and show, therefore, four discontinuities. If the contacting arrangement is parallel with the fault plane, the apparent resistivity changes gradually as the boundary is approached. Tagg has also computed the apparent resistivity curves for this case (ref. list No. $II_{10}$).

Outside of the conditions occurring in the immediate vicinity of a formation boundary, the method of resistivity mapping involves essentially only qualitative methods of interpretation, which consist, as stated before, of an interpretation of the equi-resistivity lines (Figs. 28 and 29), or of a resistivity profile (Figs. 26 and 30). In interpreting a resistivity profile, it is important to take into consideration the influence of the electrode separation, and thus of the depth penetration, for which Figure 26 is an example. Finally, in the interpretation of results obtained by resistivity mapping, tank experiments may prove to be of great value, inasmuch as they are very easily performed. The geologic bodies are usually represented by metallic conductors, and these are arranged at various depths or with varying angles of dip and strike as the case may require. Then the 4-terminal contacting arrangement is carried across the body at the surface of the water or solution in the tank, and the apparent resistivities are measured

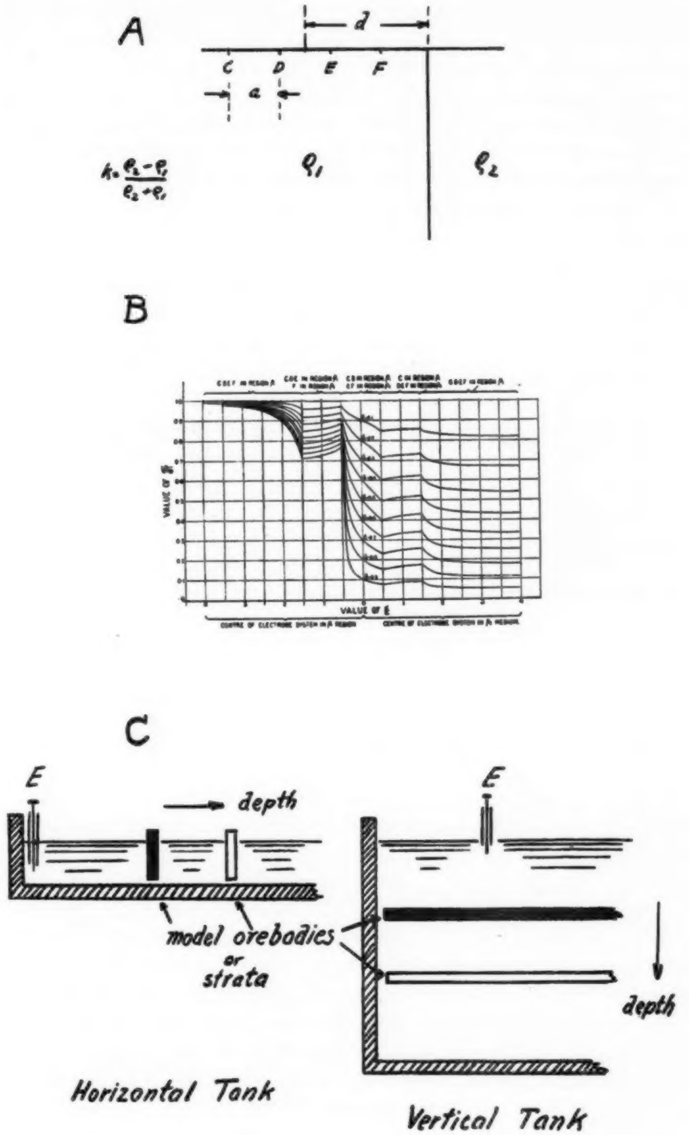



FIG. 14.—*A:* Arrangement of 4 electrodes crossing vertical boundary (after Tagg). *B:* Apparent resistivities for various electrode positions (after Tagg). *C:* Tanks used for model resistivity experiments.

and plotted. Figure 15 shows, as an example, the results of tank experiments made at the Colorado School of Mines with the objective to study the effect of dip on the equi-resistivity profiles.

The quantitative methods of interpretation are chiefly used in interpreting the results of electrical vertical drilling. The quantitative methods may be of a direct and of an indirect nature. In the direct methods, we determine the depth to formation boundaries directly

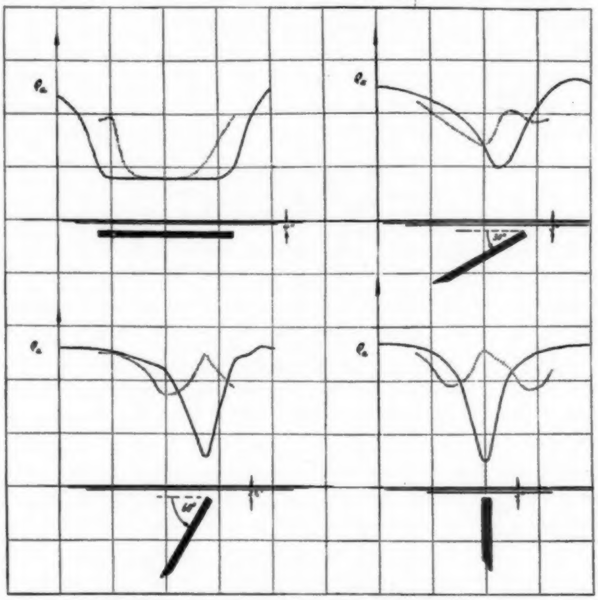


FIG. 15.—Studies of effect of dip of formation models in water tank, using 4-terminal contacting arrangement with constant electrode separation of 8 inches. *Solid lines:* Apparent resistivity when line of electrodes is parallel with strike of formation. *Dotted lines:* Apparent resistivity when electrode line is at right angles to strike.

from the curves. These direct methods are applicable in simple cases, that is, when only one formation boundary is present or possibly two. Otherwise, indirect methods are much safer; their principle is the assumption of certain formations in definite depths and a theoretical computation of the results to be expected. These results are then compared with the data obtained in the field, and the assumptions are modified until a satisfactory agreement between theoretical and

field data is obtained. In doing so, all available geological data must, of course, be considered. It may then happen that the correct interpretation is the one which does not show as good agreement between the theoretical and the field data as another assumption which is less probable for geologic reasons. It should again be recalled, in this connection, that the possibility of quantitative interpretation in electrical vertical drilling depends altogether on whether the formations involved retain their resistivities in a horizontal direction. The determinations of theoretical effects, such as involved in the indirect methods of interpretation, may not only be made by means of computation, but also by means of model experiments. For this purpose tanks may be used, filled with water or weakly electrolytic solutions, and the geologic bodies may be represented by metal plates, et cetera (for ore bodies, water tables, and faults), or by sand or clay layers. When working with metal plates it is convenient to use a horizontal tank instead of a vertical tank, that is, a tank in which the model ore bodies are moved horizontally away from the electrodes to simulate changes in depth (Fig. 14 *C*). Instead of using tanks for the model experiments, pits may be dug into the ground and filled with such alternating layers of clays, sands, et cetera, as the case may require (reference list No. $III_{33}$).[1]

Summing up the methods of interpretation applied in resistivity work, we have:

- I. Qualitative interpretation: resistivity mapping
- II. Quantitative interpretation: electrical vertical drilling
  - a. Indirect methods
    - 1. Computations
    - 2. Model experiments
  - b. Direct methods

There exists a very extensive literature on the theory of quantitative interpretation in resistivity work. The references to this literature are given in section II of the bibliography attached to the end of this paper. It is believed to be fairly complete. A perusal of this literature will show that practically the only electrode arrangement for which a complete theoretical treatment is given is the 4-terminal Gish-Rooney method, and the papers which give this theory in probably the most complete manner are those by Hummel (ref. list No. $II_{12}$), Tagg (ref. list No. $II_{10,14,16}$), Roman (ref. list No. $II_{15}$), Peters and

[1] If sand and clay layers, et cetera, are used in a small laboratory tank, the latter has to be compensated to eliminate the effects of the walls (see T. A. Manhart, ref. list No. $II_{17}$).

Bardeen (ref. list No. $II_5$), and Ehrenburg and Watson (ref. list No. $II_{11}$).

Very little is available on the theory of interpretation of results obtained by the single-probe method. It seems, however, that the results obtained by this method are generally not nearly as difficult to interpret as those obtained by the 4-terminal Gish-Rooney method. For the single-probe method in its application, illustrated in Figure 7, *IIa*, the thumb rule that the depth of discontinuities of resistivity is approximately equal to the arithmetic means of the two potential probe distances at which a marked change in resistivity is observed generally works well. This holds in particular if the distance $PR$ is much smaller than $E_1P$; otherwise, the rule that $h=\sqrt{2bc}$ should be applied. Thus, if $E_1P$ is used equal to $PR$ (method II), the depth of the geologic body becomes equal to the electrode separation at which its influence is noticed, or $h=a$.

It is beyond the scope of this paper to go deeply into the details of the theory of interpretation. However, several diagrams are given which represent the results of theoretical computations of the effect of vertical changes in resistivity on the 4-terminal method.

Figure 16 illustrates curves of apparent resistivity for the 2-layer case, and for various ratios of the resistivity of the lower layer divided by the resistivity of the upper layer. The corresponding values of $k$ mean the ratio: $\dfrac{\rho'-\rho}{\rho'+\rho}$. The observed resistivities may be plotted as ordinates, the abscissas being electrode separations; for the purposes of interpretation, however, it is more instructive to make the depth axis the ordinate and plot the observed resistivity values as abscissas, in accordance with the statement previously made that, in a general way, marked changes in resistivities occur at electrode separations $a$ which are equal to the depth $h$ of the resistivity discontinuity underneath. (Or else, this depth $h$ is by a constant ratio greater or smaller than $a$, which is taken into consideration in the diagrams, as not $h$, but $\dfrac{a}{h}$ is plotted.)

Thus, we see from Figure 16 that for all resistivity ratios the interface between surface layer and bottom layer coincides approximately with the inflection point in the curve. The abscissas, by the way, do not represent the observed apparent resistivities directly, but the ratio of the observed resistivities to the resistivity of the upper layer. For the reason just stated, the ordinates likewise do not

give depth directly, but the electrode separation or depth of penetration divided by the thickness of the upper layer. As both the resistivity and the thickness of the upper layer are constants, this method of graphical representation does not change the shape of the curves.

It is seen from the figures that in this case the boundaries of the formations underneath are reflected as points of maximum curvature, or as third derivatives of the apparent resistivity with respect to the electrode separation.

The curve denoted by "*k* equal to one" is of very great importance in practical work; it is frequently encountered in applying resistivity

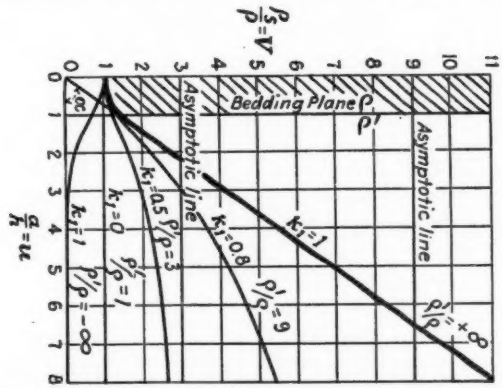



FIG. 16.—Curves of apparent resistivity over surface layer of thickness *h* for different ratios of resistivities of surface layer and infinite lower layer (after Hummel).

methods in civil engineering work and related geological problems where the thickness of the overburden above bedrock is to be determined. In such cases the resistivity of the bedrock is ordinarily so much greater than the resistivity of the overburden that the curves approach the theoretical case where the lower resistivity may be considered as infinite. For a comparison with the results obtained in practice, see the curves shown in Figure 27.

The diagrams shown in Figure 17 *a* and *b* represent the results of the theoretical analysis for the 3-layer case. In Figure 17 *a*, the second medium has the lowest resistivity; in Figure 17 *b*, the second medium has the highest resistivity. It is seen that in this case (3-layer problem) the peaks in the curves represent approximately the depth to

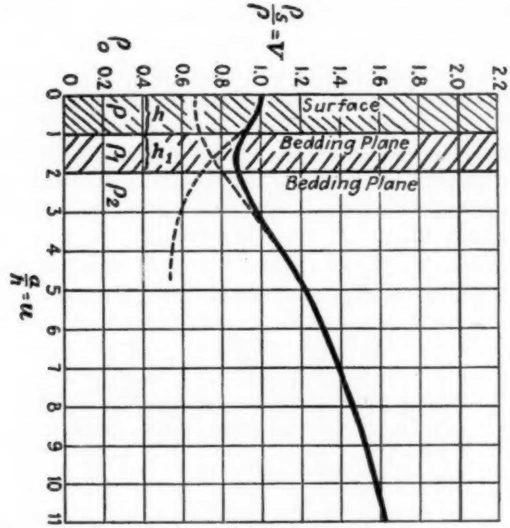



FIG. 17*a*.—Curve of apparent resistivity for case $h=h_1$ and ratio $\rho:\rho_1:\rho_2=1:0.5:2$ (after Hummel).

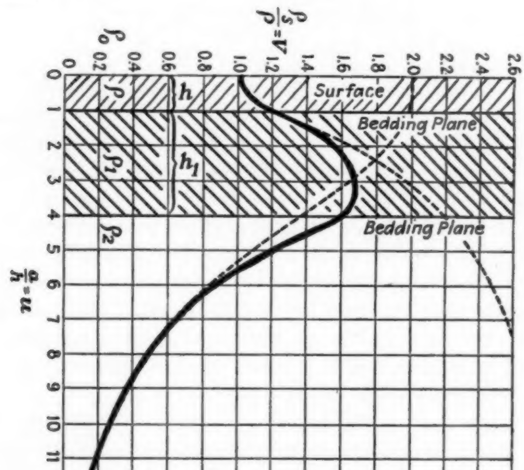



FIG. 17*b*.—Curve of apparent resistivity for case of $h_1=3h$ and ratio $\rho:\rho_1:\rho_2=1:3:0$ (after Hummel).

the center of the second medium. It is of interest to compare the theoretical curve of Figure 17 *b* with the curve obtained in actual practice shown in Figure 34.

One can readily see that already in the 3-layer case the analysis of the results obtained by the 4-terminal method presents considerable difficulties, and it is not surprising that on that account the use of this method for electrical vertical drilling has been largely abandoned and has been replaced by the various types of the single-probe method and by the potential-drop-ratio method.

Only in the 2-layer case, a rigorous direct interpretation, and a determination of the depth to the interface are possible. How this can be done in favorable geological cases, has been shown by Tagg (ref. list No. $II_{10,14,16}$).

Tagg's method is based on the following consideration. If we measure the apparent resistivity as a function of horizontal distance, the following quantities are given: the apparent resistivities as a function of electrode separation, and the resistivity of the upper layer. The ratio of the upper to lower resistivity, and the depth of the boundary are unknown. Theoretically, therefore, the equations can be solved by determining the apparent resistivities at two electrode separations. Designating by $k$ the resistivity ratio $\frac{\rho' - \rho}{\rho' + \rho}$ (Fig. 16), and by $h$ the depth to the interface, it follows that from the surface resistivity, and the apparent resistivity for only one electrode separation, $h$ as a function of $k$ can be determined and graphically represented. By taking then the apparent resistivity for a *second* electrode separation, a second function of $h$ of $k$ becomes available and can be represented by a curve, and the intersection of these two curves gives the depth. In practice, the more electrode separations used, the greater are the number of curves of $h = f(k)$, and consequently the greater the accuracy in the determination of the point of intersection of the corresponding curves.

In order to show how the interpretation is made, a practical example is demonstrated in Figure 18. In the field, the curve shown in the upper part of Figure 18*D* was obtained, indicating immediately (by comparison with Figure 16) that a poor conductor is underlain by a good conductor and that $k$ is negative. The resistivity of the top stratum is taken from the curve. If the data are not as good as they are in the illustrated case, several separate determinations may be made with small electrode separation. Then for definite electrode

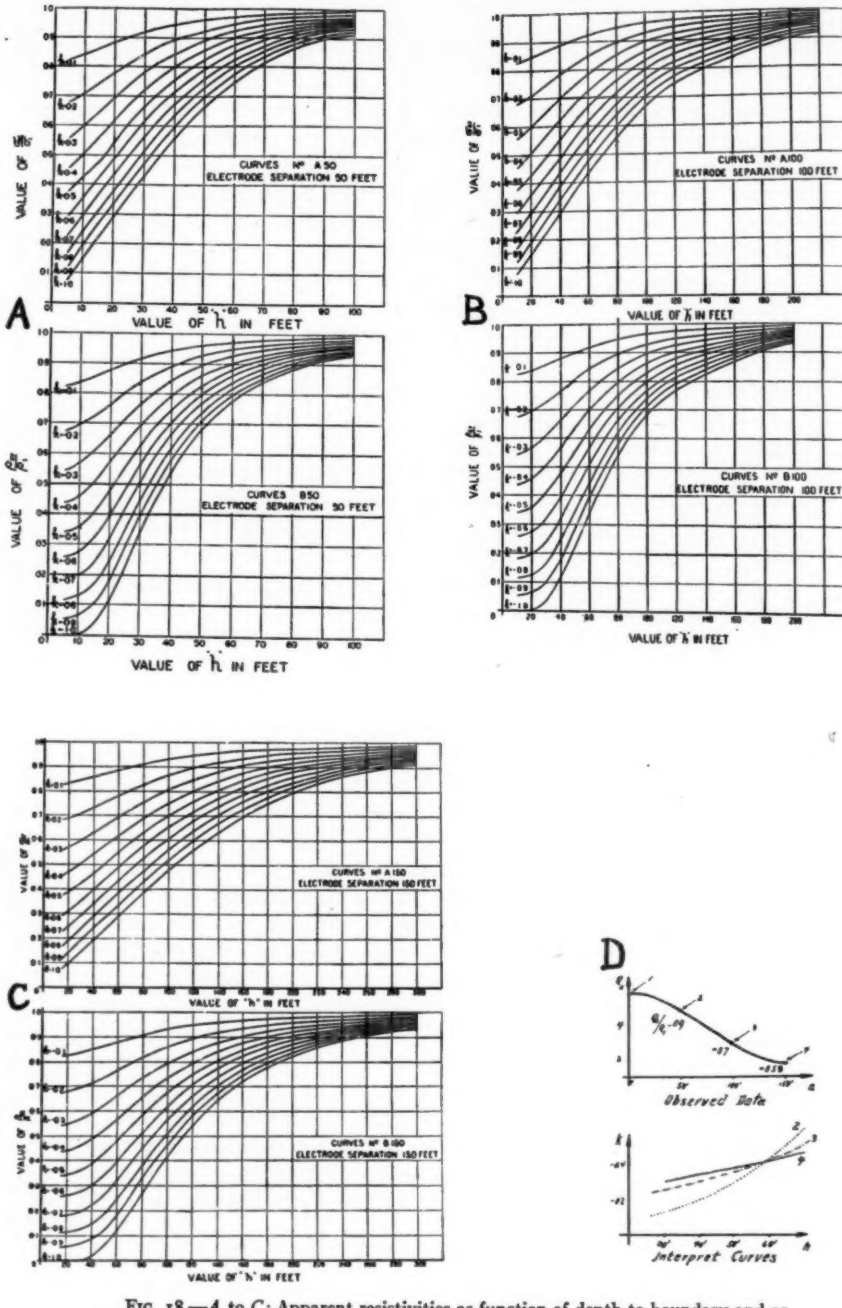



FIG. 18.—*A* to *C:* Apparent resistivities as function of depth to boundary and as function of *k*, for separations of 50,100, and 150 feet (after Tagg). *D:* Application of above diagrams in depth determinations.

separations, say for 50, 100, and 150 feet (at the points 2, 3, and 4) the ratio of the apparent resistivity to the resistivity of the upper medium is computed (Fig. 18*D*).

Diagrams have been prepared previously for this ratio $\frac{\rho_a}{\rho'}$ as a function of *h*, *a* being constant for each diagram (Fig. 18 *A–C*). (The appearance of the curves in these diagrams is much the same as those shown in the diagram of Figure 16, except that not *a/h*, but its reciprocal, *h/a* is used, and that *a* is a constant for each diagram.) In the example shown in Figure 18*D*, the ratio of apparent to surface resistivity is 0.9 for the separation 50 feet; hence, the lower diagram of Figure 18*A* is used, and the corresponding values of *h* and *k* which are intersected by the line 0.9 are noted and plotted (curve 2 in Figure 18*D*). Then the next point, $a = 100$, is taken, at which the ratio is 0.7; one proceeds as before, this time using the diagram in Figure 18*B*, and plotting *k* as a function of *h* for the ratio 0.7. This gives curve 2 in the interpretation diagram. Curve 3 is obtained in the same manner. All three curves intersect at a depth of nearly 58 feet, which is the desired depth of the formation boundary.

Under favorable conditions, this method works very well for the 2-layer case, and is often applicable in practice when the depth of overburden is to be determined. Its application, however, depends altogether on an accurate determination of the surface resistivity, which is not always easy to accomplish—or else, the resistivities determined at the surface do not represent at all the resistivity of the upper layer, the thickness of which is to be determined. In other words, the problem then is no longer a 2-layer problem.[1,2]

Schlumberger uses the following method of interpretation which deviates in a number of respects from that of Tagg's:

1) As in Tagg's method, the resistivity of the upper stratum is first determined from measurements with small electrode separations.

2) The resistivity of the lower layers is then obtained from exposures or measurements in wells (Schlumberger's "electrical coring"), or from assumptions based on past experience.

3) With these resistivities, a diagram is constructed showing the apparent resistivity as function of electrode separation in *several* curves for *a number* of values of thickness of the upper stratum.

[1] Compare also the discussion of Tagg's paper at the meeting of the American Institute of Mining and Metallurgical Engineers, February, 1932.

[2] The extension of Tagg's method to the three-layer case has recently been worked out by Manhart (ref. list No. $II_{17}$).

4) To find the thickness of the upper stratum, all that is necessary is to place the observed resistivity curve upon the one which has been computed theoretically in the manner described, and to select the

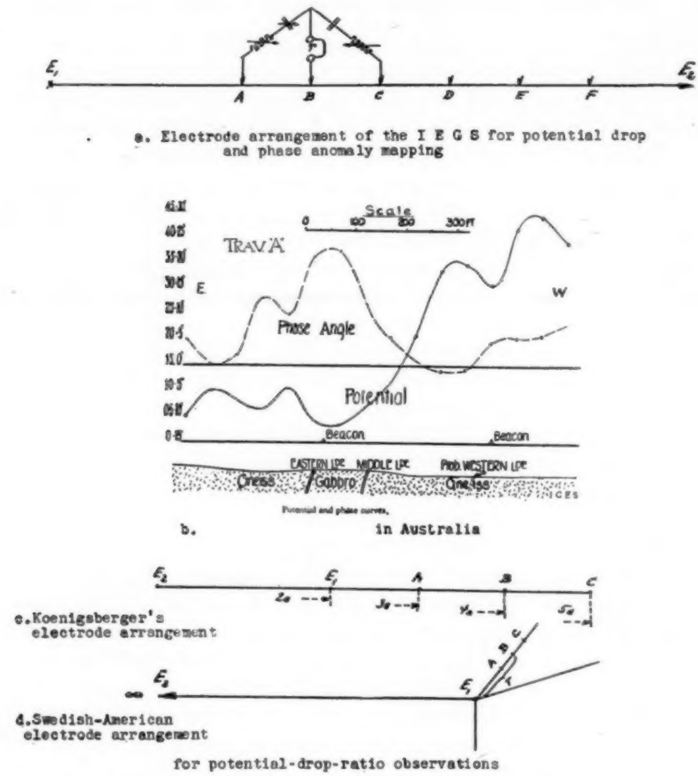



FIG. 19.—Electrode arrangements in potential-drop mapping and potential-drop-ratio work.

depth for which the observed and computed curves show the best agreement.

The same method is applicable to the three-layer case. Poldini (ref. list No. $III_{39}$) has recently demonstrated the application of this interpretation method in a number of cases.

D. Potential-Drop-Ratio Method

Although this method has been chiefly developed for the purpose of obtaining better interpretable curves in electrical vertical drilling, it may, like the resistivity method proper, be applied also in what may be termed potential-drop mapping, and phase-anomaly mapping.

As the name implies, the principle of measurement is the determination of the ratios of the potential difference between three points (Fig. 19, *a*). The instruments give the voltage difference $A-B$ divided by the difference $B-C$. It is therefore possible, by successive occupation of the points $A$, $B$, and $C$, and then of $B$, $C$, $D$ et cetera, to determine the potential drop along a traverse line. This leads to the plotting of potential-drop curves and phase-anomaly curves (Fig. 19 *b*). It is seen that the potential decreases and the phase angle increases, above conductive bodies and vice versa.[1] However, this method of plotting potentials and phases does not furnish nearly as much quantitative data in respect to depth of formation boundaries as the equi-resistivity map method (for example, Fig. 26). The information obtained by a potential and phase profile is at the present stage of interpretative technique, comparable with the information conveyed by an equipotential line map. Electrical vertical drilling by means of the potential-drop-ratio method, however, furnishes a type of curve which is most readily interpreted with reference to the depth of formation boundaries (for example, Fig. 35). While the mapping of potential drops is chiefly applicable to the detection of abrupt changes in conductivity in a horizontal direction[1] (steeply dipping ore bodies, faults, vertical formation boundaries, and the like), the potential-drop-ratio method is to be given preference when the depth to horizontal formation boundaries is determined. Figure 20 shows this advantage of the potential-drop-ratio method by a comparison of the indications obtained by it with the type of curves furnished by: (*a*) equipotential line, (*b*) potential drop, and (*d*) apparent resistivity methods. It is seen that the interpretation of the potential-drop ratios becomes particularly easy if the curves shown under (*c*) are turned through 90°, that is, if the geologic section is plotted in the usual manner, with the exception that the vertical scale is stretched to 3/2 of the original scale, and the electrical curve is superimposed upon it. We shall return to this method again when dealing with the interpretation of the potential-drop-ratio indications.

[1] See also Hedstrom (ref. list No. $IV_7$).

low resistance lower medium

high resistance lower medium

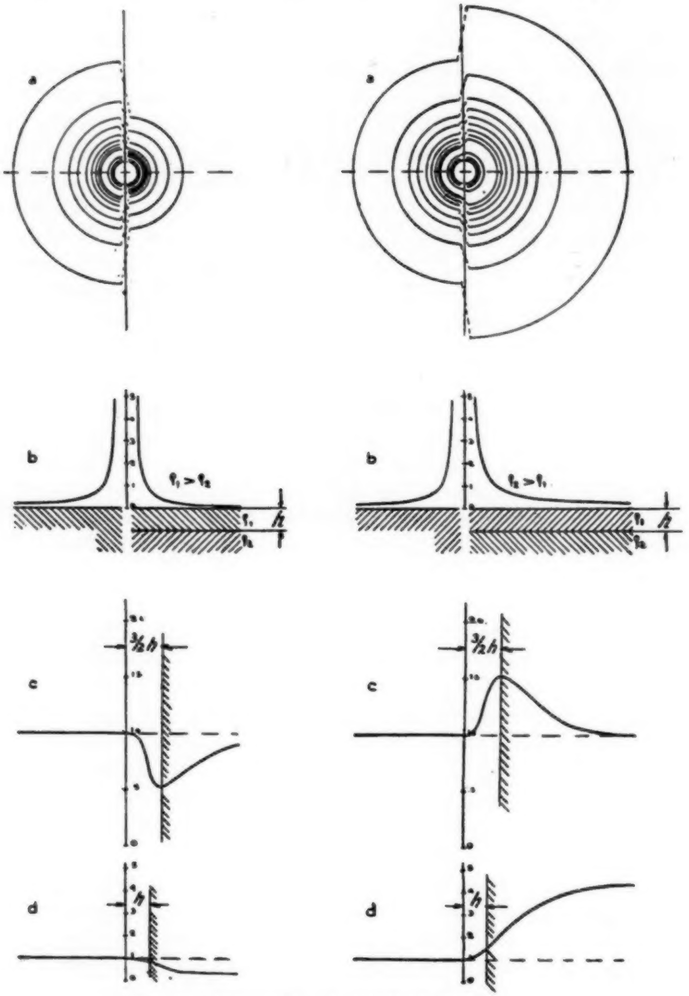



FIG. 20.—Comparison of potential indications:

*a:* Equipotential lines
*b:* Potential drop
*c:* Potential-drop ratio
*d:* Apparent resistivity
(after Lundberg & Zuschlag)

## I. ELECTRODE ARRANGEMENTS

### *a.* IN POTENTIAL-DROP AND PHASE-ANOMALY MAPPING

The arrangement customary in this work is shown in Figure 19*a*. Current from an A.C. source, that is, either from a generator or from a buzzer, is supplied to the ground at the points $E_2$ and $E_1$. The potential drops are measured between the power electrodes, at the points $A$, $B$, $C$, $D$, $E$, et cetera, and the bridge arrangement occupies first the points $A$, $B$, and $C$; then the points $B$, $C$, and $D$; then $C$, $D$, and $E$, et cetera. The procedure is accurate but laborious. For the reasons just stated, that is, that the potential-drop indications are more pronounced for vertical formation boundaries than for horizontal ones, this method of potential mapping has not found very much application in oil work. Only vertical electrical drilling by means of the potential-drop-ratio method has gained importance.

### *b.* ELECTRODE ARRANGEMENTS FOR ELECTRICAL VERTICAL DRILLING

The two types which have been used to date are illustrated in Figure 19 *c* and *d*. The electrode set-up used by Koenigsberger differs from the arrangement employed by the Swedish American Prospecting Company in that the spacing of the current electrodes is changed, while in the Swedish American arrangement the current basis remains constant. Furthermore, in Koenigsberger's arrangement the current basis is short and only twice as long as the interval of the search electrodes $A$, $B$, and $C$ while in the Swedish method the exploring electrodes are used in the vicinity of one current electrode and the other current electrode is practically at infinity. Finally, in the Swedish American arrangement the interval between the exploring electrodes remains fixed, while in Koenigsberger's method this interval increases with an increase in the length of the current basis. Hence, for purposes of interpretation, the depth reached in Koenigsberger's method is a function of the interval $a$, while in the Swedish method the depth is proportional to the distance of the center probe, $B$, from the power electrode $E$. In Koenigsberger's method the measurements are made in the extension of the current basis; in the Swedish American method, the traverses may be laid so as to radiate in all directions from the near power electrode; to eliminate the influence of the far current electrode completely, the most advantageous arrangement is at right angles to the current basis (strictly on the circumference of a circle with the radius $E_1E_2$ about the far current electrode).

## II. APPARATUS

### a. GENERAL: POWER SOURCES

Potential-drop-ratio measurements may be made with both D.C. and A.C. Koenigsberger has used both types of current, while the Swedish American employs only A.C. If D.C. is used, a number of B-batteries are sufficient, if the required depth penetration is not great. Otherwise, a gasoline engine D.C. generator is more advantageous for greater depth of exploration. The current should be interrupted by a commutator similar to the one employed in the Gish-Rooney apparatus, so that effects of polarization and stray currents are eliminated. As will be stated later, the Gish-Rooney equipment itself may be employed for potential-drop-ratio determinations (with slight modification) for simple problems, although the accuracy furnished by the potentiometer customarily employed in this apparatus is not sufficient for many purposes.

For the potential ratiometers as used by the Imperial Geophysical Survey and the Swedish American Prospecting Company, alternating current of about 500 cycles is required, which for small depths of penetration is furnished by a buzzer operated from a storage battery (Fig. 23) while for greater distances and unfavorable contact conditions, a 500 A.C. generator is preferable. It must be borne in mind, however, that the use of a stronger power source alone with average frequencies does not bring about a greater depth penetration, as the latter decreases with the frequency employed; hence, for great depth penetrations, the frequency has to be considerably lowered, which then also would require a change in the dimensions of resistances and inductances in the ratiometers, or else commutated D.C. should be used.

### b. KOENIGSBERGER'S AND OTHER D.C. METHODS

Koenigsberger indicates in his publication (ref. list No. $IV_2$) in a general way a number of arrangements which he has used for the measurement of potential-drop ratios, but does not go into details with reference to apparatus employed. When using D.C., the potential differences $A-B$ and $B-C$ may, of course, be measured independently by a potentiometer and their ratio may be formed by computation. For this purpose, a regular Gish-Rooney equipment may be employed, with an electrode arrangement identical with that used in the single-probe method (Fig. 7, type *IIa*). The potential difference between the points $B$ and $C$ is measured in the usual way; then

the electrode in $C$ is left there and the electrode which was at $B$ is moved to a next point, say $D$, which has the same distance from $C$, as $B$ has from $C$. The curves shown in Figure 33 have been obtained in this manner. The method is not very accurate, as the surface and contact resistances enter considerably.

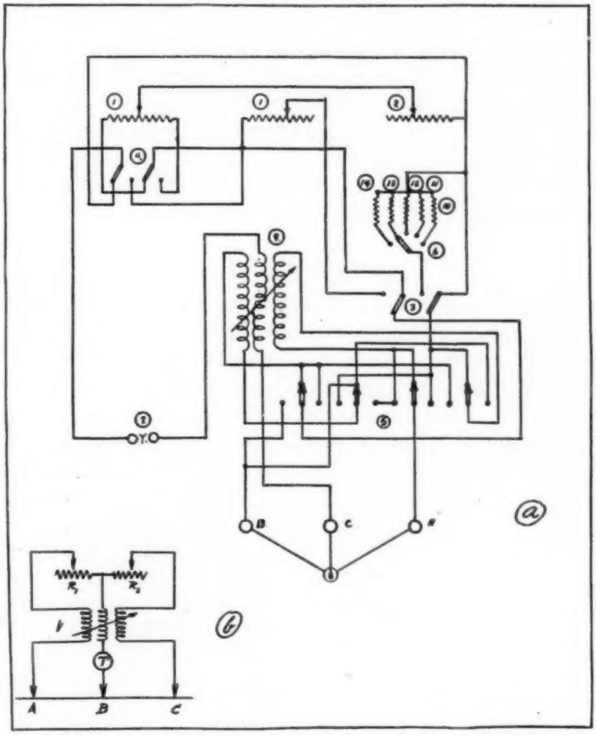



FIG. 21
*a:* Detailed circuit diagram of Racom compensator
*b:* Schematic circuit diagram of same

Koenigsberger uses also a modification of this method: The central electrode is left permanently connected to the potentiometer and the other electrodes, $B$ and $C$, are connected alternately with it by means of a commutator. The ratio of the deflections gives the potential

drop ratio; or else, it is possible to leave one electrode, say $C$, stationary, and change the position of the other until a balance is obtained.

A still better arrangement would be the bridge shown schematically in Figure 21*b*, when modified for direct current: the variometer $V$ would be left out, and the telephone $T$ would be replaced by a sensitive galvanometer.[1] To overcome the contact resistance at the probes, two settings of the resistances $R_1$ and $R_2$ would be required. If commutated D.C. is used, the commutator could be incorporated in the bridge. This would necessitate a lead from the bridge to the power source. In order to eliminate this lead, very low frequency A.C. could be supplied to the power stakes, and a rectifier could be used with the galvanometer.

In addition to D.C., Koenigsberger has also used A.C. with bridges similar to the arrangements now to be described.

### *b.* SWEDISH AMERICAN RACOM

The name Racom is an abbreviation for ratio compensator. The principle of the instrument is a compensation of the difference of the potential $P_{A-B}$ and $P_{B-C}$ between the three points $A$, $B$, and $C$, by adjusting resistances in the two circuits $AB$ and $BC$ to balance on a telephone. Alternating current of about 500 cycles is used, and for small depths is furnished by a buzzer, operated from a storage battery, shown in Figure 23. A schematic circuit diagram is given in Figure 21, *b;* as seen from the figure, the current in the circuit $AB$ is equal to $\frac{P_{A-B}}{R_A+R_1}$, and the current in the circuit $BC$ is equal to $\frac{P_{B-C}}{R_C+R_2}$, where $R_A$ and $R_C$ are the contact resistances of the stakes $A$ and $C$. As the resistances $R_1$ and $R_2$ are so adjusted that the telephone is silent, we obtain the equation for the potential-drop ratio $\frac{P_{A-B}}{P_{B-C}}=\frac{R_A+R_1}{R_C+R_2}$. The contact resistances may be eliminated by a second setting of $R_1$ and $R_2$. The phase differences are compensated by a suitable setting of the variometer, $V$. If the observed currents are too feeble to be heard on the telephone an amplifier is employed, as shown in Figure 22. A schematic diagram and a detailed circuit diagram are given in this figure. The amplifier is a 2-stage, resistance-

[1] A similar arrangement is used for pipe-line corrosion studies by Schlumberger (ref. list No. $III_{40}$).

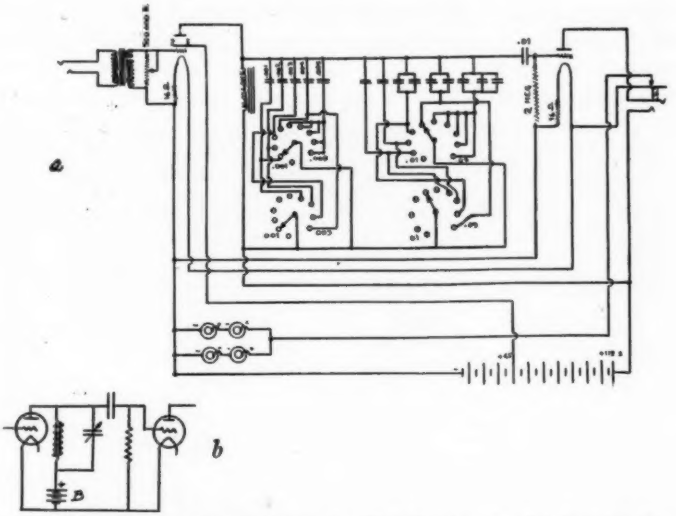



FIG. 22.—*a:* Wiring diagram, Racom amplifier. Courtesy Swedish American Prospecting Corporation. *b:* Schematic diagram.

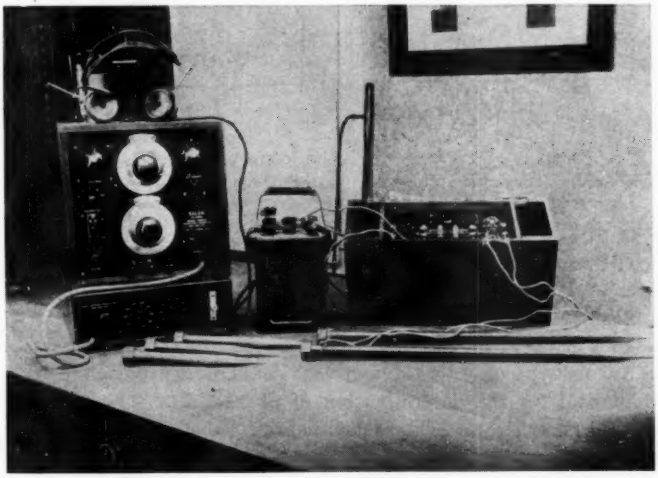


FIG. 23.—View of Racom with amplifier and buzzer.

impedance-coupled amplifier, incorporating a tuning of the choke for the elimination of harmonics so as to enable a better setting of the bridge.

Figure 23 shows a view of the Racom, with amplifier underneath the instrument box, and a buzzer on the side together with the power and the exploring electrodes.

For more details on the operation of the Racom and examples of a number of surveys, see Lundberg and Zuschlag's publication on the subject (ref. list No. $IV_5$).

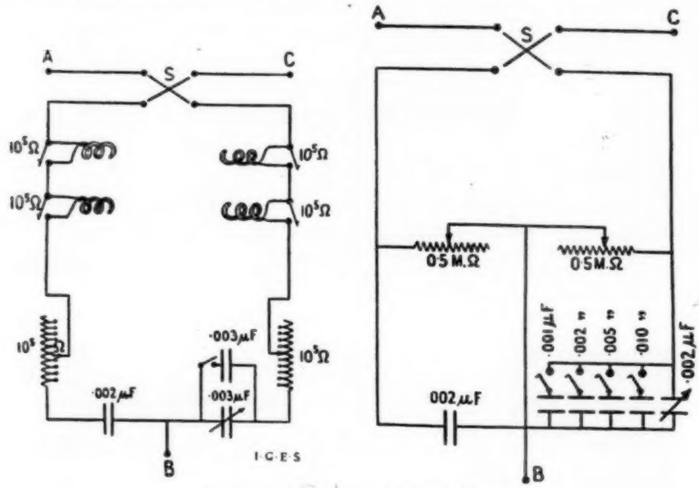



FIG. 24.—I.E.G.S. ratio arm bridges.
FIG. 24*a*.—Series ratio arm bridge. FIG. 24*b*.—Parallel ratio arm bridge.

### *d*. I.G.E.S. RATIO COMPENSATORS

The potential ratiometers used by the Imperial Geophysical Experimental Survey in Australia are very similar in design to the Swedish American bridge just described. A schematized view of their bridge is given in Figure 19 *a*. It is seen that this bridge differs from the Racom type only by the fact that condensers are used instead of inductances for the determination of phase shifts. The wiring diagrams for a series and a parallel ratio arm bridge are shown in Figure 24. Figure 25 gives a view of the panel of one of these bridges. An amplifier is also used in conjunction with these bridges, and in the field is carried by means of straps on the operator's back. For details

on the operation of these ratiometers and their theory, the publication by Edge and Laby (pp. 50–54, and 268–274) (ref. list No. $IV_3$) should be consulted.

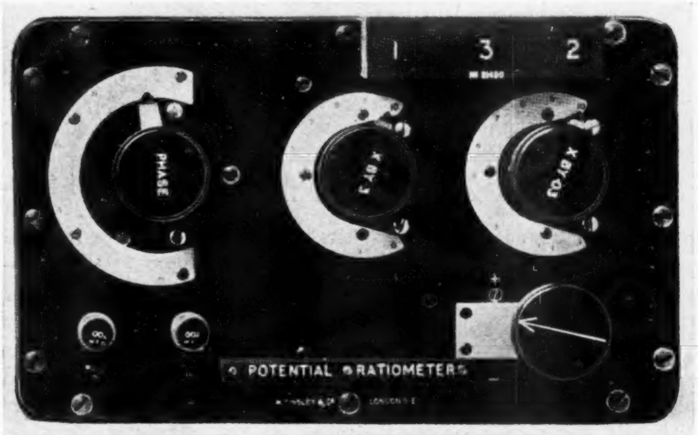



FIG. 25.—View of I.E.G.S. ratio compensator.

### III. INTERPRETATION

Methods of interpretation of potential-drop-ratio results have been worked out in a general way for Koenigsberger's and for the Swedish American methods.

The results of the computations show that Koenigsberger's method is, in a number of ways, at a disadvantage as compared with the Swedish method, because his ratios are only opposite but not equal for good and poor conductors which have the same conductivity ratio. What is meant by this is the following: If we form, for a 2-layer problem, the ratio of the conductivity of the surface layer to the conductivity of the lower layer, then the potential-drop ratio in Koenigsberger's method is 3.57 if the conductivity ratio is one (homogeneous ground). However, if the conductivity ratio is 10:1, the potential ratio decreases only to 2.48, whereas, in the converse case (if the conductivity ratio is 1:10) the potential ratio is 8.70 (Fig. 40 *c*). Thus, it is seen that in his method the potential-drop-ratio responses are not symmetrical around the 3.57 position, and that the influence of good

conductors below is much greater than the influence of poor conductors below. This would make this method a rather valuable accessory to the Racom, if it is desirable to emphasize in the results the effects of good conductors, such as ore bodies or formations which are filled with salt waters.

Figures which give the general values for the potential ratios in the Racom method have not been published, but it appears from the diagrams given by Lundberg (Fig. 20) that for the average conductivity ratios the potential-drop-ratio responses are approximately the same for a good conductor below as they are for a poor conductor below; for, as seen from Figure 20, for the assumed conductivity ratio, the potential ratio is 1.5 for a good conductor above and 0.5 for a good conductor below; or, the deflections in the Racom method are equal and opposite for equal and opposite conductivity ratios. Hence, when plotting in the Racom method the potential ratios on a vertical axis and the formation boundaries in a horizontal position, a poor conductor manifests itself by a deflection of the ratio curve toward the right, and a good conductor appears as a deflection of the ratio curve toward the left. For a poor conductor below, the ratio is greater than one, and for a good conductor below, the ratio is smaller than one.

The chief advantage of the potential-drop-ratio method lies in the ease with which the potential ratio indications, if plotted in a suitable manner, may be interpreted with reference to the depth of formation boundaries. Although the potential-drop ratios, and hence also the relations between depth of boundary and maximum of indication, depend on the conductivity ratios of the formations involved, yet several empirical rules have been found to hold very well for the average conductivity ratios encountered in the field.

In Koenigsberger's method, the depth corresponding with a ratio maximum is approximately $\frac{1}{2}$ *a* for conductivity ratios up to 1:10 or 10:1. In the Racom method, the depth to the formation boundary is, under similar conditions, equal to $\frac{2}{3}$ *r*. (The significance of the symbols is explained in Figure 19.) Hence, when we turn the ratio traverses through 90° and plot the curves vertically on a geologic section, we have to stretch the vertical scale of the section to 3/2 in the Racom, and double it in Koenigsberger's method. Or, if we want to leave the scale of the geologic section as it is, we have to reduce the distances in Koenigsberger's method to $\frac{1}{2}$ and the distances in the Racom method to $\frac{2}{3}$ of their original values. These relations are well

explained in the practical examples illustrated in Figures 33, 35 and 40.

### E. Opinions Regarding Direct Electrical Prospecting for Oil

In view of the recent developments of the technique of resistivity and potential-drop-ratio-measurements which permit (as has been shown and can be verified by an inspection, for example, of Figures 34 and 35) the accurate identification of certain geologic horizons under favorable circumstances, the question becomes, of course, acute again as to the extent to which oil deposits may be located directly by electrical measurement from the surface.

Very much has been written about this subject, probably altogether too much at a time when field technique and interpretation of electrical prospecting were not nearly far enough developed to enable anyone involved in the discussion to state definitely that certain things were altogether impossible. The writer believes that several authors who were involved in the animated discussion at that time wish now, in view of the recent developments, that they had not voiced their opinion in the matter.

Another factor which influenced the exchange of opinions in the problem of the possibility of locating oil directly was the fact that most of the involved parties were interested in competitive geophysical consulting companies. Hence, the writer doubts if very much could be gained by repeating in detail at this time all the arguments which have been advanced for and against the direct electrical location of oil. Only the main points will be discussed. At any rate, it is emphasized that it is not the object of this paper to take sides in an argument which is not as yet ripe for an altogether unbiased discussion. We shall not try to decide at this time if a direct location of oil by electrical prospecting is possible. We shall merely state, by discussing actual results obtained, what has been done and can probably be done with the present state of development of instrumental technique and interpretation. The whole discussion in this matter seems to have been started when the representatives of the Elbof electrical prospecting company claimed that they were in a position, by means of their method, to locate the oil directly. The chief factor which probably encouraged doubts and discussions of their statements was the fact that the type of indications which they obtained by means of their method, namely the deflection of current lines, did not lend itself very readily to such far-reaching interpretations. In fact,

even under favorable geologic conditions, the deflections of the current lines were usually small and therefore the claimed effects could be readily disputed. In addition, this company made their claims on the basis of some work which was carried out at comparatively great depth and under complex geologic conditions, so that it was easy for their opponents to go so far as to state that there was no telling whether the observed deflections came from salt water or from oil.

The opponents of the Elbof theory, notably Ambronn, then went to the other extreme in trying to prove that it was theoretically impossible, under any circumstances, to detect oil directly with alternating current. Ambronn claimed that the conductivity ratio required for electrical prospecting by means of alternating current should be at least 1,000 for such a change to be detectable, a figure which has been proved to be much too high by actual experience obtained since with the potential and resistivity methods. In addition, Heine and Hunkel proved theoretically that the formulas used by Ambronn for his proofs were in error.

Lately, the Elbof company has also taken up, in addition to their electromagnetic method, the study of the potential-drop-ratio and resistivity methods; the results obtained in several areas have been published by Gella and Koenigsberger (ref. list $III_{23}$; $IV_2$). Unfortunately, in both publications, no curves are given and this is probably the reason why these more recent claims of the Elbof company and Koenigsberger, which are based on reliable and favorable technique, have passed almost unnoticed. The figures given for the results obtained with the potential drop ratio at the oil field of Oberg in Germany are given in such manner that the reader who is not familiar with the locality can not form an opinion as to the extent to which the claims advanced are justified. The writer has made an attempt to use as many of Koenigsberger's data as possible and to superimpose them upon the geologic section; the results are represented in Figure 40 and are discussed at the end of this paper.

While working with the potential-difference method, the Elbof company found that in certain areas where the oil-bearing strata are overlain by porous strata such as sands and sandstones, the gas had in many places migrated into them from the strata below, had displaced the salt water and had thus increased considerably the thickness of the strata acting as poor conductors. This may make it possible in some places to apply the electrical method to advantage, but it is,

on the other hand, a condition which is by no means representative of all oil reservoirs.

A rather serious argument has been advanced lately by Hedstrom (ref. list No. $III_{21}$) against the direct electrical prospecting for oil. This author claims that from theory and experiment it follows that a formation which is practically an insulator does not show in the electrical results any differently from what it would if its conductivity were only 10 times smaller than that of the surrounding formation; hence, a poorly conductive sand or limestone with a conductivity only about 10 times less as compared with that of the surrounding strata, would not be distinguishable from the effect of an oil formation.

This argument, however, does not preclude the possibility of direct location of oil in an area where, by correlation with geologic data, a poor conductor is known to be oil bearing, and where it would thus be possible to trace this oil-bearing horizon in various depths of structure, and to determine where the filling of the pores with oil ceases and where the oil is replaced by salt water. If the argument just advanced is correct, it would seldom be possible to distinguish between a sand filled with gas or a dry sand, and a sand filled with oil.

One might finally say in commenting on Hedstrom's argument, that with a greater perfection of technique of electrical prospecting we may some day be able to distinguish the surface effects of poor conductors with a greater precision and obtain an electrical log in which the formation resistivities could be represented by their true and not their apparent resistivity, so that an oil sand would show somewhat like the sands illustrated in the electrical logs demonstrated in Figure 37 and Figure 38.

However, as already stated, it is beyond the scope of this paper to take sides in this argument, and we will merely confine ourselves to a discussion of the results thus far obtained in attempting to locate the oil directly at the end of the following section (F II).

## F. Results Obtained With Resistivity and Potential-Drop-Ratio Methods

### I. IN STRUCTURAL WORK

Several outstanding examples are here described which illustrate both the possibilities and the limitations of the resistivity and potential-drop-ratio methods in determining geologic structure.

### a. DETERMINATION OF THICKNESS AND CHARACTER OF SURFACE FORMATIONS

The chief potentialities of both the resistivity and the potential-drop-ratio methods lie in the determination of character and depth to formation boundaries of surface formations. In general, as in any other geophysical method, the thickness of geologic formations has to compare favorably with their depth, otherwise they may pass unnoticed in resistivity indications; on the other hand, conditions for recognizing formation boundaries are much more favorable in the potential-drop-ratio method than they are in the resistivity methods. In addition, a reason why these methods lend themselves so readily to the determinations of depths and thicknesses of surface formations is the fact that they often differ much more in their resistivity from the underlying series than these lower formations will differ between themselves.

A problem which often arises in practical geology is the determination of the thickness of glacial overburden. Both the method of resistivity mapping and the method of vertical electrical drilling can be applied to advantage, depending on the problem.

Thus far, the majority of examples for the determination of the thickness of surface formations have become known from applications in mining and civil engineering, but they would also be of importance in certain types of oil-structural work.

#### 1. BY EQUI-RESISTIVITY MAPPING

A rather convenient way to map bedrock contours in a fairly large area, or to determine the depth to bedrock along a traverse line, is to carry a 4-terminal contacting arrangement with fixed electrode separation over the area and to observe and plot apparent resistivities in the manner shown in Figure 26. The results obtained with two electrode separations are illustrated. The solid contour represents the depth to bedrock, the dashed line is the indication obtained with the correct electrode separation, and the dotted lines show the apparent resistivities with too small electrode spacing. The geologic section was glacial drift above limestones and conglomerates. This figure shows that with an electrode separation larger than the greatest depth to bedrock, the bedrock contour may be mapped with a good deal of accuracy.

#### 2. BY ELECTRICAL VERTICAL DRILLING

This method has been applied very frequently in late years in determining the depth to bedrock in tunnel and dam sites. Figure 27

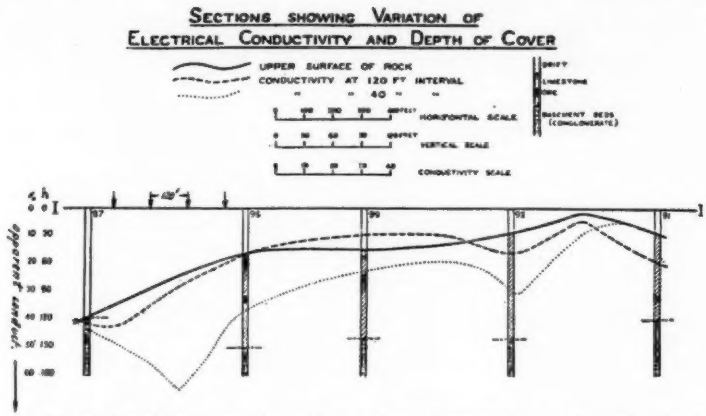



FIG. 26.—Resistivity mapping with two electrode separations to determine depth of cover (after Lancaster-Jones).

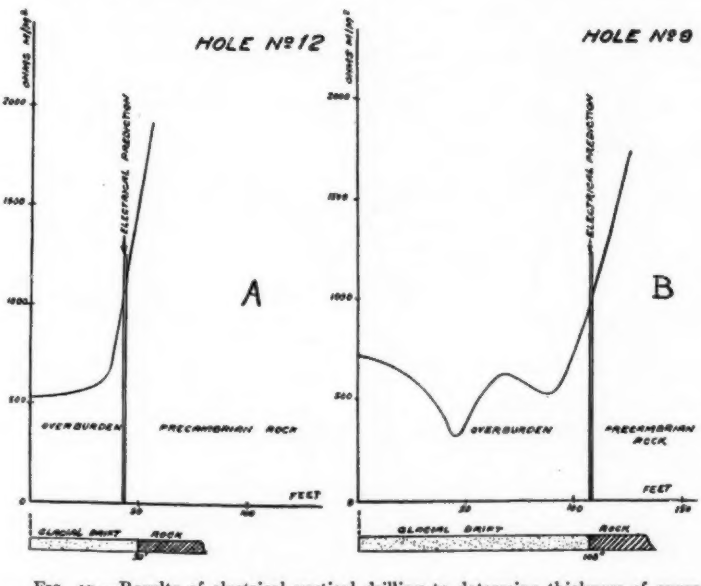



FIG. 27.—Results of electrical vertical drilling to determine thickness of cover (after Leonardon).

*A:* Diagram in case of fairly homogeneous overburden. Accuracy fairly satisfactory.

*B:* Form of results when overburden is composed of different layers.

shows two resistivity profiles with the corresponding drilling results. In interpreting the resistivity curves, reference should be made to the curves shown in Figure 16 for the case in which the resistivity of the lower layer is practically infinite. The two curves shown in Figure 27 also illustrate the effect of a homogeneous and an inhomogeneous overburden.

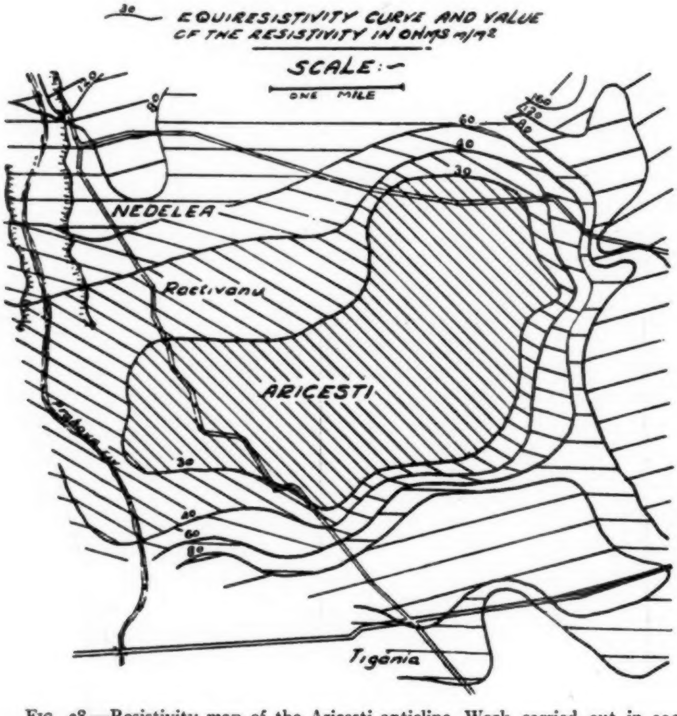



FIG. 28.—Resistivity map of the Aricesti anticline. Work carried out in 1923 (after Schlumberger).

3. BY POTENTIAL AND PHASE MAPPING

This method will probably find little application in oil structural work, although it can give valuable indications in determining the character of surface formations in suitable areas under a shallow cover. Figure 19 shows, as an example, the effect of a gabbro intrusion with two ore bodies on the contact zone upon the potential-drop and

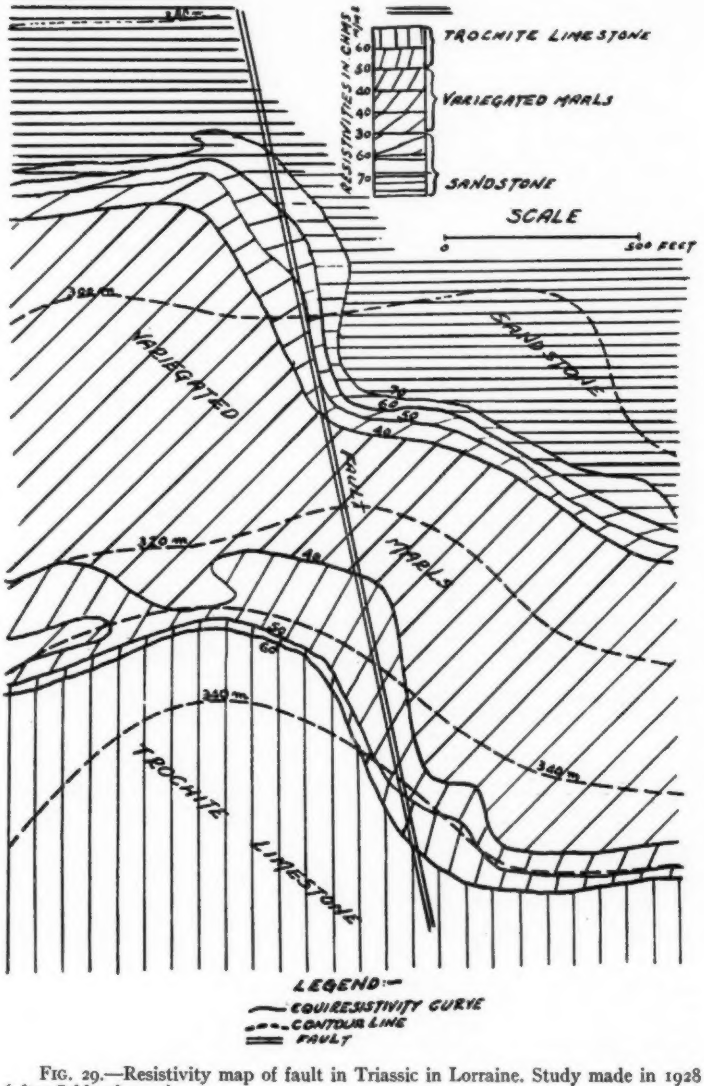



FIG. 29.—Resistivity map of fault in Triassic in Lorraine. Study made in 1928 (after Schlumberger).

phase curves. It will be noticed that the potential decreases above a good conductor, while the phase angle has a maximum, and vice versa.

### b. LOCATION OF STRUCTURE

Both resistivity and potential-drop-ratio methods have found already several remarkable applications in locating geologic structure favorable for the accumulation of oil, such as anticlines, salt domes, and the like. They have also been applied very successfully in extending known geologic information into unknown territory, which is an application always recommended for any kind of geophysical method.

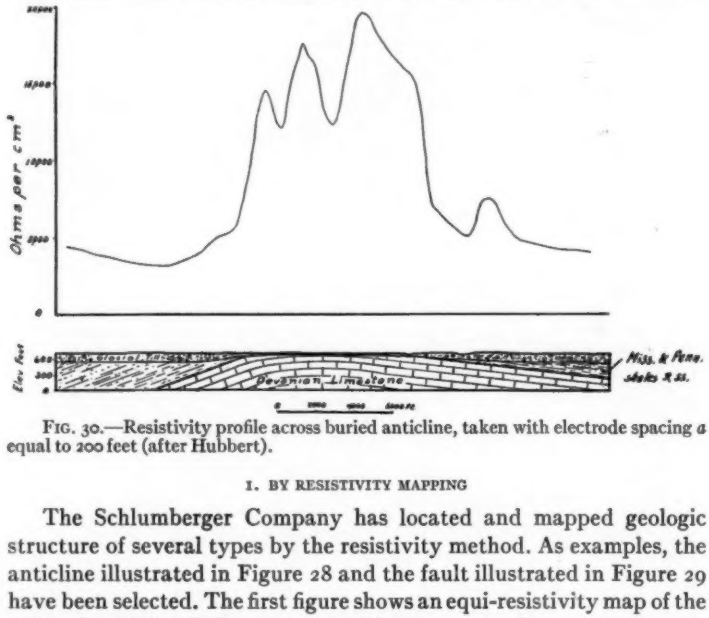



FIG. 30.—Resistivity profile across buried anticline, taken with electrode spacing $a$ equal to 200 feet (after Hubbert).

#### 1. BY RESISTIVITY MAPPING

The Schlumberger Company has located and mapped geologic structure of several types by the resistivity method. As examples, the anticline illustrated in Figure 28 and the fault illustrated in Figure 29 have been selected. The first figure shows an equi-resistivity map of the Aricesti anticline in Roumania which appears in the resistivity map as a body of lower resistivity. Very instructive is the location of a fault in Alsace-Lorraine by the method of resistivity mapping, as it illustrates how definite resistivity values may be identified with definite geologic horizons. The marls have the lowest resistivity, then follow the limestones, and then the sandstones in this area. The resistivity contours follow truly the trace of the fault which has displaced the formations under discussion in a horizontal direction.

Figure 30 shows another good example of structure located by means of a resistivity profile. The traverse was made with a 4-terminal contacting arrangement using an electrode interval of 200 feet. As this interval is greater than the greatest thickness of the glacial till in the area, the observed apparent resistivities represent chiefly the variations in resistivities below the glacial drift. Thus it was possible to get the effect of the anticline composed of Devonian limestone of high resistivity, flanked by Mississippian shales and sandstones of lesser resistivity. Hubbert states that the causes of the smaller variations in the resistivity peak are unknown; it is probable, however, that they

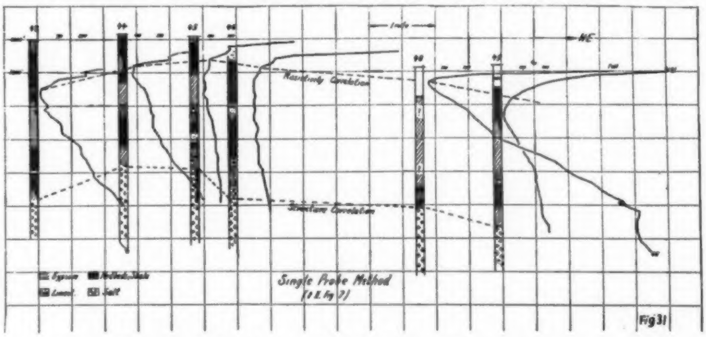



FIG. 31.—Results of electrical vertical drilling with single-probe method (II) and corresponding geologic section in an area in New Mexico. Courtesy of Harry Aurand, Midwest Refining Company.

are either due to variations in the composition of the glacial till, or due to the fact that this till occurs as filling in erosion channels on top of the structure.

2. BY ELECTRICAL VERTICAL DRILLING

There follows now a discussion of some examples of structural resistivity work, most of which were obtained recently and may not be found elsewhere in the geophysical literature. They illustrate well the great possibilities of the method of electrical drilling with the resistivity and potential-drop-ratio method under favorable conditions.

Figure 31 shows the results of several resistivity traverses which were very carefully measured every 10 feet by means of the single-probe method (No. II of Hummel in Figure 7 or the Ehrenburg-Watson method). The geologic section consists at the surface of alternating shale, gypsum, and limestone beds with an average thick-

ness of 400 feet underlain by salt. The resistance of the gypsum is high, and that of the shales is low. Where the effect of the salt has been picked up, its resistance seems to be fairly low, such as shown in well No. 48, which is somewhat contrary to the experience obtained on salt domes. All resistivity traverses shown in Figure 31 have a similar appearance as far as the very high resistance surface layers are con-

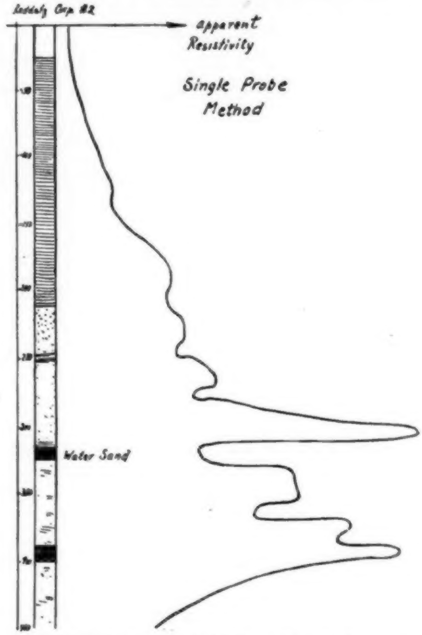



FIG. 32.—Results of electrical vertical drilling using single-probe method (II*a*) and corresponding well log at Berthoud dome, Colorado. (Measurements made by Keen, Bishop, and Johnson.)

cerned. Then they all show a pronounced "low," corresponding with the influence of the red beds and shales close to the surface. After that, all curves go up again, depending on the amount of gypsum present in the section. Thus, while the curves of Nos. 45 and 46 are practically flat, they are steeper in 49, 44, 43, and steepest in 48. Just what takes place in No. 48 is not very well known on account of lack of knowledge of the well log; but it seems that the formations present at that locality, probably gypsum, are very poor conductors. A striking similarity

prevails between the curves of 43, 44, 45, and 46. Particularly, 43 is very similar to 44, and 45 very similar to 46. Corresponding with the bottom of the first red-bed layer, all the curves mentioned have the same appearance, which becomes less pronounced toward the northeast, but may yet be recognized very faintly in curve 49. Therefore,

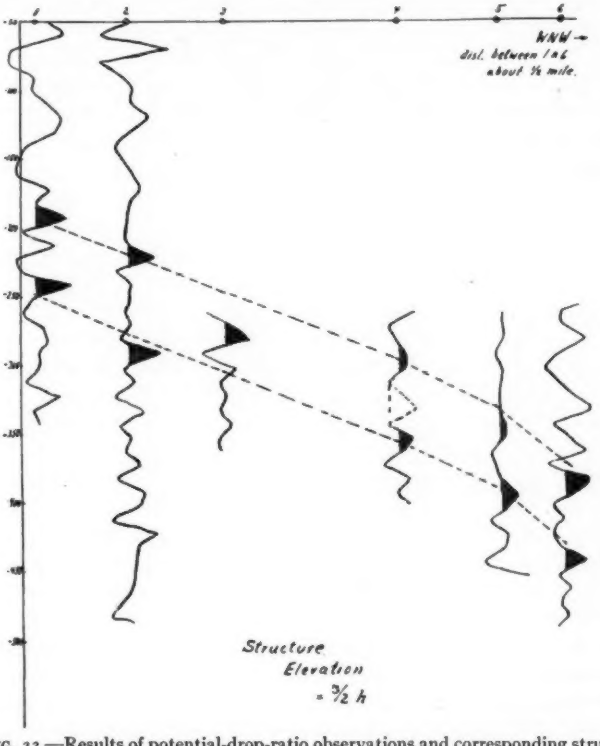



FIG. 33.—Results of potential-drop-ratio observations and corresponding structure at Berthoud dome, Colorado.

the writer has used that particular part of the curve as horizon marker for the resistivity correlation. It is seen that the resistivity contour thus obtained is not everywhere in accord with the logs, but that it checks very well with the structure correlation made on top of the salt beds. The next two figures, 32 and 33, show some results which were obtained with the single-probe and the potential-drop-ratio

methods on the Berthoud dome, not far from Denver. Some oil and gas have been produced from this dome. The geologic section consists of Cretaceous shales and sands. The curve shown in Figure 32 was obtained by using the method No. *IIa* (Fig. 7), and is plotted together with the log of a well next to which the measurements were made. Pending further work in this area, the present interpretation is that the peaks in the curve are produced by the water sands, and that these sands contain water of artesian origin, which is encountered in geologic structure of many types in eastern Colorado near the Front Range of the Rocky Mountains. If nothing else, this curve shows that certain resistivity peaks appear at certain depths which can be correlated with definite geologic horizons, and which can be traced throughout the structure.

This makes it possible to determine structural contours in this area as shown in Figure 33. It should be understood that these results were obtained with an equipment which was not at all adequate for the purpose. Before the regular Racom equipment (already described) became available for field work, we made some preliminary field tests with the Gish-Rooney apparatus modified for the determination of potential-drop ratios. Hence, the results are masked to some extent by the variations in surface resistivities which can be eliminated to a much greater degree in the Racom. Nevertheless, the results are reliable enough to justify at least a preliminary interpretation. The potential-drop-ratio curves were turned 90° and plotted vertically. It is seen that certain peaks in the curves repeat themselves in every traverse, and these are indicated in solid black. Then the structural contour as known from the well logs was superimposed upon the potential-drop-ratio profiles, and was plotted on a scale 3/2 that of the potential profiles, in accordance with what has been previously stated about the interpretation of potential-drop-ratio measurements. It is seen that the known structural information and the peaks in the potential-drop-ratio profiles correspond fairly well. In this connection, it should be remembered that the indications obtained from a potential-drop-ratio log in electrical vertical drilling are altogether different from the indications obtained in a resistivity log. In the former, formation boundaries are marked by a peak in the drop-ratio curve (Fig. 20).

Although the results just described are not as good as they might have been if more adequate equipment had been used they proved definitely that the potential-drop-ratio method could be used to ad-

vantage in eastern Colorado, in close conjunction with geologic data, for the purpose of obtaining data about geologic structure.

Figure 34 shows again some resistivity curves, obtained on four traverses in the San Fernando Valley in California. The results of this work were published by J. J. Jakosky (ref. list $III_{31}$) in different form; it appears from the description of the work that some sort of a single-power-probe method was used. It may be possible that the 5-electrode system described by Jakosky[1] in a later paper was employed, on which no data are at present available, and which may be some sort of potential-drop-ratio method with an electrode arrangement similar to that shown in Figure 19 or may be the partition method (Fig. 7, *Ia*).

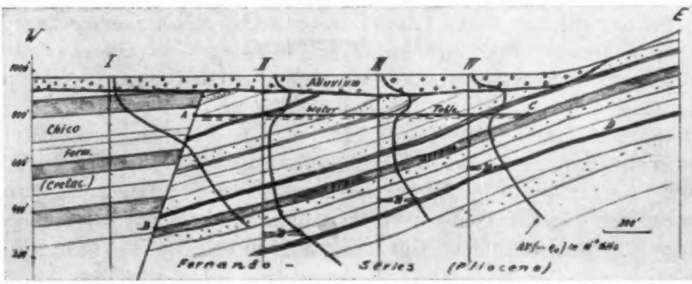



Fig. 34.—Results of four resistivity traverses (single-probe method) and corresponding geologic section in San Fernando Valley, California. (Plotted from data published by J. J. Jakosky.)

As stated by Lundberg and Zuschlag (ref. list No. $IV_5$) apparent resistivities may also be readily computed from the potential-drop ratios.

In Figure 34, the results obtained by Jakosky are shown, plotted in millivolt units which are directly proportional to the apparent resistivity. The geologic conditions are as follows. The larger part of the area is covered by a blanket of alluvial strata with a maximum thickness of nearly 80 feet. Below, in the eastern part of the area, are inclined strata of the Fernando group of the Pliocene. These formations are cut off by a fault in the western part of the area which has brought strata of the Cretaceous Chico formation in contact with the Pliocene in the east. These Cretaceous strata do not contain water, but the upper parts of the Pliocene are filled with highly conductive waters down to a depth where the impervious strata indicated as

[1] J. J. Jakosky, "Geophysical Examination of Meteor Crater, Arizona," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., 1932), pp. 63–98.

such in the figure occur. As the Pliocene strata are cut off in the west by the fault, a conductive triangle, so to speak, occurs between the points *A*, *B*, and *C*. Below the line *BC*, the strata are less conductive, and the same is true of the strata above the water table. Due to the absence of water west of the fault in the Cretaceous section, these strata also are poor conductors.

The resistivity profiles *II*, *III* and *IV* are similar to each other, but differ greatly from the profile I. They indicate a high resistance peak, corresponding with the Quaternary top layer and the Fernando strata above the water table. Then the resistivities drop to very low value, corresponding with the depth of the conductive triangle which is involved in every case. Thus, the horizontal part of the resistivity curve indicating the part of this triangle traversed by each traverse, is very short in traverse *IV*, longer in *III*, and still longer in traverse *II*. As soon as the impervious strata are reached, the resistivity curves go up again, this rise occurring at the shallowest depth in traverse *IV*, being deeper at *III*, and the deepest in traverse *II*. In other words, the point where, on each curve, this rise begins, gives approximately the depth, and thus the dip of the impervious formations. The agreement with the geologic section goes still further. After the impervious layer has been traversed in each section, the recorded resistivities are in proportion with the resistivities of the section below this impervious series. Thus, if we take a certain point on each curve, for example, those corresponding with a deflection of 20 millivolts, and connect these points, the resulting line gives directly the dip of the strata below the impervious layers.

The resistivity curve obtained at the traverse *I* indicates formations of much higher resistivity than the curves obtained on the other traverses. The peak corresponding with the dry layer above the water table which was obtained on the other traverses is also missing. A distinct break occurs in this curve which is explained by the fact that the apparent resistivity drops when a depth is reached which is equal to the horizontal distance (at that depth) of a better conducting medium from the traverse line. We, therefore, interpret this break in the traverse *I* as the effect of the strata east of the fault plane.

In Figure 35, the results of two potential-drop-ratio traverses across an area in the Spring Coulee district in Alberta are shown. The geologic section is Cretaceous below glacial drift, the Cretaceous being alternating shales and sandstones of the St. Mary and the Fox Hills formations. The measurements are made with a Racom equip-

ment by the Swedish American Prospecting Corporation. As seen from Figure 20, in electrical vertical drilling by the Racom method, formation boundaries are represented by peaks in the ratio curves. Plotting the data as done in Figure 35, that is, ratios higher than one, on the right, and ratios lower than one, on the left, a comparison with Figure 20 shows that a peak on the right means a poor conductor below that peak, and a peak on the left means a good conductor below the peak. Thus it is readily seen that the sandstones are poorer conductors than the shales, which is in accordance with an observation which was

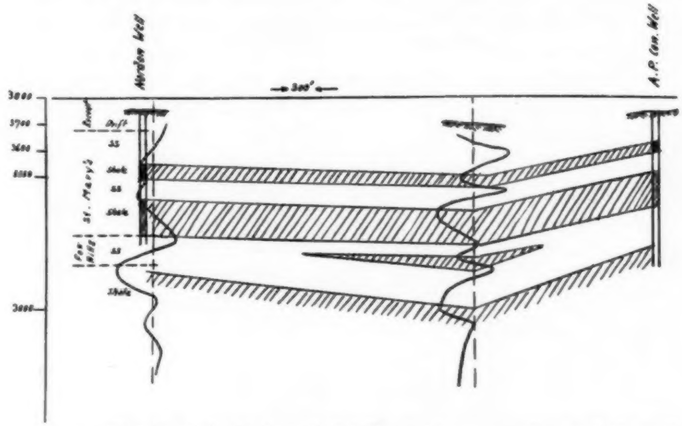



FIG. 35.—Results of electrical vertical drilling and corresponding geologic section at Spring Coulee, Alberta, Canada. Potential-drop-ratio method was used. (From pamphlet of Swedish American Prospecting Corporation.)

previously made when discussing the results represented in Figure 31. It is also seen from Figure 35 how well the electrical results check the well data and how the electrical vertical drilling by means of the potential-drop-ratio method may be used to advantage in carrying the structural data obtained from wells into unknown territory.

### 3. RESISTIVITY CORRELATION IN WELLS

In discussing the results which have been obtained on structure with the resistivity and potential-drop-ratio methods the experience obtained by measuring resistivities in wells should by no means be overlooked. In the first place, the results obtained by determining the resistivities *in situ* at the depths reached by the drill, give very

important information for the interpretation of resistivity measurements made at the surface. Secondly, the systematic "electrical coring" makes it possible to correlate wells by their "resistivity log" in much the same manner as it is possible by the sample log, and gives

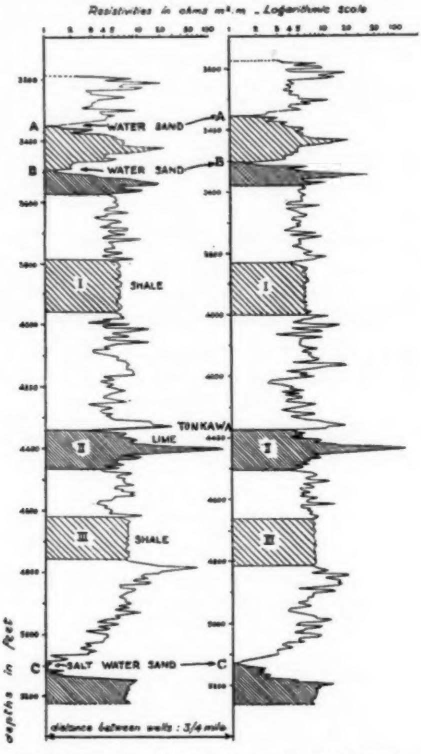



FIG. 36.—Electrical correlations between two wells, Oklahoma City, 1929. (Waters No. 3 and Mackey No. 1.)

not only a possibility for structural correlations, but at times enables one to recognize beds which may otherwise be overlooked.

Figure 36 represents two resistivity logs obtained with the Schlumberger method of electrical coring in two wells ¾ mile apart near Oklahoma City. In this figure, the resistivities are plotted in logarithmic scale. It is seen that the two curves are very similar in almost

every minute detail. All other formations except the shales exhibit rather irregular characteristics which makes it possible to correlate definitely the shale horizons in the two wells. Water sands are characterized by very low resistivity; the resistivity of the water sand at the bottom of the holes is almost nil. The Tonkawa limestone shows by a pronounced and characteristic resistivity peak.

## II. DIRECT LOCATION OF OIL

There are two possibilities of locating oil directly or of distinguishing oil-bearing formations from barren strata: first, by resistivity measurements in wells; and second, by resistivity measurement at the surface. The former method has proved its merit almost everywhere it has been applied, but the second possibility has not yet been established as a commercial method, and only with exceptionally favorable conditions have direct indications been obtained from oil-bearing formations where they were known to exist at shallow depths.

The possibility of obtaining a direct indication from an oil-bearing horizon in a well does not only mean the possibility of tracing this same oil formation in another well; but, as experience has shown, it is possible to determine where this oil formation becomes barren or changes into salt water in other wells (which is of practical importance in deciding the depth of water shut-off), as well as how thick and how prolific an oil sand is, the information on the productivity being a valuable guide which can not be obtained from the drill record.

### I. RESISTIVITY MEASUREMENTS IN WELLS

Figure 37 illustrates without further comment how much more resistant oil-producing formations are than non-productive formations. This figure is an example of a resistivity log taken in the Seminole area, the two sands being saturated with heavy oil. It is seen that the resistivities measured are much higher for oil-bearing beds than for highly resistant, compact sedimentary formations. In case of doubt the ambiguity can be eliminated by simultaneous records of porosities, the technique of which is described in Schlumberger's paper on electrical coring (ref. list $I_{11}$).

Figure 38, representing several electrical logs taken in the Maracaibo field, not only illustrates very well the possibility of resistivity correlations of the oil beds directly in adjacent wells, but also shows how the resistivity of an oil bed changes if it passes from the productive to the non-productive stage. The upper tar sand and the first

productive horizon both are seen to decline rapidly in resistivity toward the edge of the productive zone.

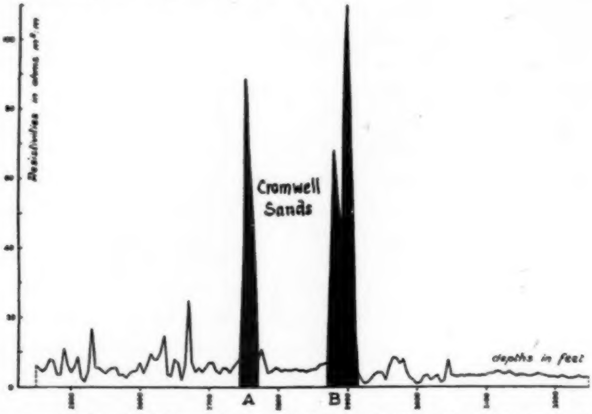



FIG. 37.—High resistivity of two producing sands, Wewoka field, Seminole area, Oklahoma, 1929. (Peney Reed No. 1.) (After Schlumberger.)

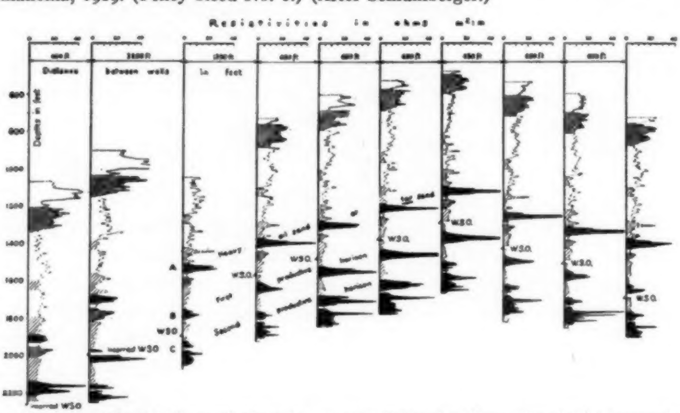


FIG. 38.—Electrical correlations between wells in the Maracaibo field, Venezuela. (After Schlumberger.)

2. ELECTRICAL VERTICAL DRILLING IN DIRECT PROSPECTING FOR OIL

If it is possible to recognize oil-bearing beds in wells in such indisputable manner, is it not possible to get the same or similar results by measurements from the surface? The results obtained thus far in approaching a solution of this problem will now be discussed.

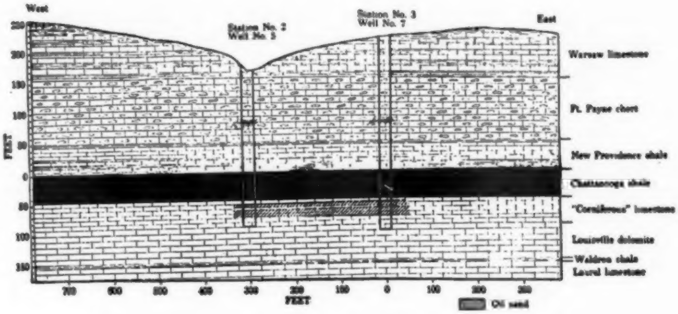



FIG. 39 *a*.—Geological section in Allen County, Kentucky.

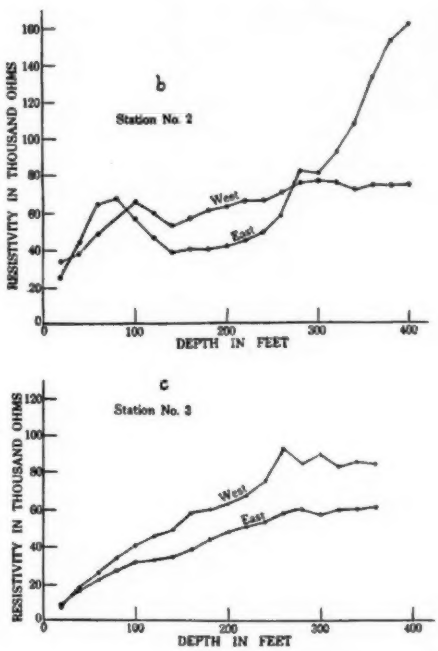



FIG. 39 *b* and *c*.—Resistivity traverses (partition method) at same locality (after Lee and Swartz), showing differences of resistivity between east and west at station 2 and station 3.

The writer knows of only two[1] instances where it is claimed that it was possible to recognize a direct effect of the oil in the resistivity data (in this paper we shall not deal with the claims which have been

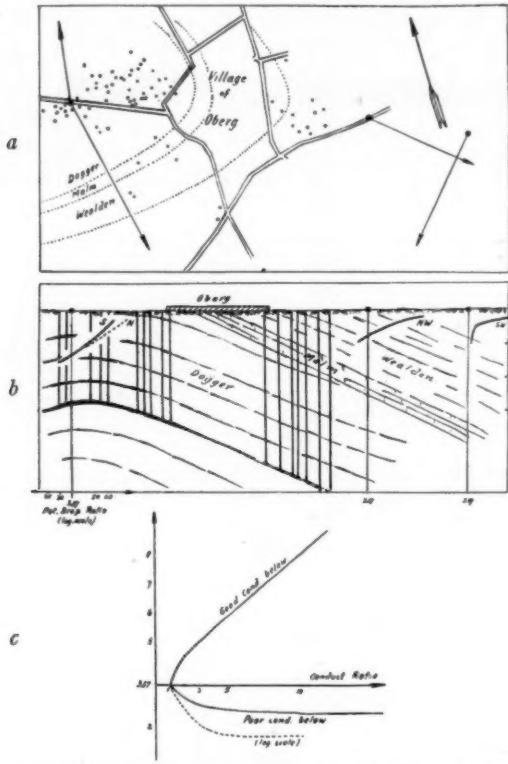



FIG. 40 *a* and *b*.—Results of some potential-drop-ratio measurements, and corresponding geologic section, in Oberg oil field, Germany. (Plotted after data published by J. Koenigsberger.) *c:* Potential-drop ratios as function of conductivity ratio.

made in that respect for the electromagnetic Elbof method). The first of the two instances in question has been published by Lee and Swartz, the second by Koenigsberger (ref. list Nos. $III_{19}$, $III_{37}$, and $IV_2$).

[1] As a possible third instance may be mentioned the measurements carried out by Swartz and others to determine the depth of rock asphalt in very shallow depth (ref. list No. $III_{29}$, p. 114). The observations were made in the same area in which indications from oil-bearing strata in 5–800 feet depth, to be described later, were obtained.

Koenigsberger has published results obtained along three potential-drop-ratio traverses in the Oberg field in Germany, of which only the ones measured on the extreme west and the ones measured on the extreme east side of the field lend themselves to graphical representation. The location of these traverses is shown in Figure 40 *a*. By designating with Koenigsberger the interval between the power electrodes by $2a$, results are available in this author's publications for intervals $a$ equal to 100, 200, and 300 meters for the southern part, and for the intervals of 50, 100, and 200 meters for the northern part of the traverse on the west side of the field, while the distances used were 50, 100, and 200 meters in both traverses on the east side of the oil field. The productive zone is located on the west side of the area, and the oil is taken from a depth of approximately 300 meters from strata of the lower part of the middle Jurassic, while in the central part of this area the productive zone is nearly 500 meters in depth. At the locality at which the eastern traverses were made, the lower Dogger strata presumably contain salt water instead of oil.

From the foregoing figures for the distances used, it is seen that potential-drop ratios are given only for four (or three, respectively) depths in the western and for three depths in either traverse on the east. Koenigsberger states in his publication that the depth corresponding with the potential-drop-ratio indications is $h = \frac{1}{2} a$, and the observed potential-drop-ratio values have been plotted in the middle part of Figure 40 in accordance with this depth rule. As for normal ground the ratio is 3.57, values greater than this ratio have been plotted at the right, values smaller than this value were plotted at the left. As seen from Figure 40 *c*, the indications obtained from poor conductors are not nearly as pronounced as the indications from good conductors below; in order to equalize the indications somewhat, the logarithmic scale was employed to draw the curves shown in Figure 40 *b*.

Koenigsberger, in his article, now makes the statement that "the influence of insulating formations is quite evident from the fact that the ratio drops below 3.6 in the traverse on the west side."

The writer does not see how the observed values can possibly be correlated with the productive area, as the electrode spacing used was in all cases too small to penetrate down to the oil-bearing formations. On the other hand, it is true that some oil occurs in this field above the productive zone in the strata of the lower Dogger (that is, in depths less than 300 meters) and it is also possible that the diffusion

of gas from the productive layers into the upper strata, which has been previously mentioned, has replaced all salt water and has made the strata poor conductors. At what depth this zone begins would be difficult to state as the curves are not complete enough to draw such conclusions. If this assumption is correct, it follows that the electrical characteristics of the Wealden can not be much different from those of the Dogger, as the curve observed in the northwest profile in the east is not much different from the curve observed in the west traverse. It actually appears from geologic reports that the Wealden is also oil bearing in this area and contains a heavy oil which is not exploited, and it is further seen from the results that, if such an oil horizon exists below the locality of the northwest part of the east profile, this horizon is at shallower depth at this point than it is in the west. The southwest part of the east traverse does not show an influence of poor conductors at the depths reached.

As a whole, the data published by Koenigsberger appear to be far too meager to permit very far-reaching conclusions. They do not seem to indicate that it would be possible with his method to differentiate a poorly conductive sedimentary stratum devoid of oil, from a stratum which is saturated with oil. It is possible that Koenigsberger has used greater electrode separations and thus greater depths of penetration in addition to those for which results have been published, and it is possible that the results obtained at greater depth substantiate his statements. However, the published data do not corroborate them, and the writer doubts very much that, if the illustrated results had been obtained in areas in which the presence of oil was not known, anybody would have seen anything unusual about them.

The second instance where a direct location of oil by a resistivity method has been described offers much more concrete information. The results in question were obtained on a site in Kentucky, the geology of which is shown in Figure 39 *a*. Lee's partition method was used, and the curves obtained when going to either west or east of both stations 2 and 3 are illustrated in Figure 39 *b*. The depth of the oil zone from the surface was in this place, however, much less than the depth of the oil zone on which Koenigsberger did his work; it was only 250–300 feet, while the depth of the productive oil formations in Koenigsberger's experiments was about three times as great. The oil zone occurs in the form of an oil sand between wells 2 and 3. Actually, east from station 2, the observed resistivity values were greater than those on the west, and the converse holds for station 3;

toward the east, the resistivities become smaller than the values obtained toward the west.

This is the only place at which, to the writer's knowledge, it has been definitely established that the oil can be located directly by surface resistivity measurements.

After this article was written, Swartz (ref. list No. III$_{37}$) published the results of further resistivity measurements in Kentucky. In the recent observations, the depth of the oil-bearing sands was much greater than in the determinations discussed above; it varied between 500 and 800 feet. It was found that generally the resistivity curves rose where oil and gas were present and fell where dry territory was encountered. One case is cited where predictions as to the occurrence of hydrocarbons made on the basis of resistivity determinations were checked later by drilling with striking accuracy. Furthermore, in the area of the Legrande pool, the boundary of the dry and producing area could be outlined from the resistivity data and checked the information obtained from wells. The striking fact about this boundary is that it is not marked by edge water, but by a decrease in porosity with corresponding decrease in the oil and gas content: another fact worth mentioning is that the best indications were obtained from a gas sand only 4 feet thick in a depth of about 640 feet; that is, the sand detected was only 0.6 per cent of the depth.

The author concludes that "for the partitioning method the shielding effect of such low resistivity beds as are encountered in oil and gas fields are negligible as far as the detectability of underlying gas and oil horizons is concerned," and continues as follows: "It is feasible to locate oil and gas zones, as well as salt water zones, *directly* by resistivity measurements on the surface of the ground. Whether such beds can be detected under all conditions and at all depths is, of course, not at present known. So far it is safe to say only that for depths up to 1,000 feet and under the physical and stratigraphic conditions here obtaining, such beds may be determined with excellent accuracy."

### G. Summary and Conclusions

Resistivity and seismic refraction methods have several physical characteristics in common. They both involve the advantage of controlling the depth of penetration and thus a greater definiteness of interpretation than obtained in other geophysical methods. On the other hand, they are largely subject to the same limitations as other

methods, namely, that the depth of geologic bodies must compare favorably with their size or thickness. The resistivity methods have been applied for some time in oil work, but interest in them has been aroused of late due to the perfection of technique which makes it possible to obtain a type of indication which may be interpreted more readily (the potential-drop-ratio method).

Although the determination of actual resistivities of samples is not a factor as important in resistivity work as the determination of related physical properties in other geophysical methods, remarkable progress has been made in the design of apparatus which permits the determination of resistivities on samples in the field and in the laboratory, and on outcrops of geologic formations.

The requirements on instruments and technique are not excessive in resistivity and potential-drop-ratio work; for moderate depth of penetration, moderate power sources are sufficient. The equipment for the determination of resistivities and potential-drop ratios is readily portable and easily operated. In both resistivity and potential-drop-ratio work, two distinct fields of application may be distinguished; first, the method of resistivity mapping, and second, the method of electrical vertical drilling. For the former, the 4-terminal Gish-Rooney equipment with one or two fixed electrode separations is usually employed, while for the electrical vertical drilling any one of the methods in resistivity work, and three potential electrodes near one power electrode in potential-drop-ratio work, is employed.

The results obtained thus far indicate that it is possible to locate readily geologic structure with the method of equi-resistivity mapping at not too great depth, and that detailed information may be obtained at any one point by the method of electrical vertical drilling with a fairly great degree of accuracy down to a depth of 1,500 feet with the present state of the technique, under favorable circumstances.

While remarkable progress has been made in identifying and correlating indications due to oil beds in wells, the location of oil directly by measurements from the surface is still in its very early stages of development, and there is only one case where the direct location of oil in very shallow depth from the surface by electrical measurement has been definitely established.

The resistivity methods depend probably more than any other geophysical method on a very good correlation of the geophysical data with known geological results, and their chief application is

given where the problem is to extend the structural information in a known area into adjacent territory.

The chief obstacle which now faces the direct electrical location of oil is that, with our present technique, we can not detect a perfect insulator any better than a stratum, the conductivity of which is only approximately 10 times smaller than that of the adjacent beds. However, there is no reason why in the near future the methods can not be perfected to such an extent that, when a resistivity indication has been definitely established to be due to an oil bed in a certain depth, this indication can be traced into adjacent territory with the object of determining whether or not the oil is replaced by salt water. It is doubtful, however, whether or not the reverse will be accomplished so soon, as it is difficult, *at the surface*, to distinguish a dry resistant formation from an oil-bearing bed. In problems of the type just discussed, that is, in tracing a formation with the object of determining whether its contents change from oil to salt water, the potentialities of the resistivity and potential-drop-ratio methods will probably be utilized to the greatest advantage when the resistivity indications are combined with results obtained from other geophysical methods which would give the structural data alone, such as the seismic reflection method.

## REFERENCE LIST

(References are arranged according to date of publication, under four headings.)

### I. RESISTIVITIES OF ROCKS AND FORMATIONS; DETERMINATIONS OF SAME

1. R. O. E. Davis, "The Use of the Electrolytic Bridge for Determining Soluble Salts," *U. S. Dept. Agriculture Circ. 427* (Washington, D. C., July, 1927).

2. B. McCollum and K. H. Logan, "Practical Applications of the Earth Current Meter," *U. S. Bur. Standards Tech. Paper 351* (August, 1927).

3. R. D. Harvey, "Electrical Conductivity and Polished Mineral Surfaces," *Econ. Geol.*, Vol. 23, No. 7 (November, 1928).

4. W. Heine, *Elektrische Bodenforschung*, Gebr. Borntraeger (Berlin, 1928), 223 pp.

5. J. Koenigsberger, "Field Observations of Electrical Resistivity and Their Practical Application," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., New York, 1929), pp. 221–37.

6. M. W. Pullen, "Tentative Method for Making Resistivity Measurement of Drill Cores and Hand Specimens of Rocks and Ores," *U. S. Bur. Mines Circ. of Inf. 6141* (June, 1929), 11 pp.

7. J. G. Biddle, "Megger Ground Tester," *Cat. 1750* (Philadelphia, October, 1929).

8. C. and M. Schlumberger, "The Electrical Coring," *Soc. de Prospection Électrique* (Paris, September, 1929).

9. Karl Sundberg, "Principles of the Swedish Geo-Electrical Methods," *Gerland's Beitraege Supp. Applied Geophys.*, 1, No. 3 (1931), pp. 298–361.

10. ———, "Effect of Impregnating Waters on the Electrical Conductivity of Soils and Rocks," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., New York, 1932), pp. 367–91.

11. C. and M. Schlumberger, and E. G. Leonardon, "Electrical Coring; A Method of Determining Bottom-Hole Data by Electrical Measurements," *Amer. Inst. Min. Met. Eng. Tech. Publ. 462* (New York, February, 1932).

12. S. F. Kelly, "A uniform expression for resistivity," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., New York, 1932), pp. 141–43.

II. THEORY OF RESISTIVITY METHODS

1. Frank Wenner, "A Method of Measuring Earth Resistivity," *U. S. Bur. Standards Ser. Paper 258; ibid. Bull. 12* (4) (October, 11, 1915), pp. 469–78.

2. Warren Weaver, "Certain Applications of the Surface Potential Method," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., 1929), pp. 48–87.

3. F. W. Lee, J. W. Joyce and Phil. Boyer, "Some Earth Resistivity Measurements," *U. S. Bur. Mines Inf. Circ. 6171* (October, 1929).

4. C. Schlumberger, *Étude sur la prospection électrique du sous-sol*, 2nd ed. (Gauthier-Villars, Paris, 1930), 96 pp.

5. L. J. Peters and John Bardeen, "The Solution of Some Theoretical Problems Which Arise in Electrical Methods of Geophysical Exploration," *Univ. of Wisconsin Bull. Eng. Exper. Station*, Ser. 71 (Madison, 1930), 88 pp.

6. S. Stefanesco and C. and M. Schlumberger, "Sur la distribution électrique potentielle autour d'une prise de terre ponctuelle dans un terrain homogène à couches horizontales, homogènes et isotropes," *Le journal de Physique et le Radium* 7, 1 (4) (1930), pp. 132–40.

7. J. N. Hummel and W. Heine, "Die elektrischen Methoden der angewandten Geophysik," *Handbuch der Experimentalphysik*, Vol. 25, No. 3 (1930), pp. 401–518.

8. W. Weaver, "Mathematics and the Problem of Ore Location," *Amer. Math. Monthly*, Vol. 37 (April, 1930), pp. 165–81.

9. E. Lancaster Jones, "The Earth Resistivity Method of Geophysical Prospecting," *Mining Mag.*, Vol. 42, No. 12 and Vol. 43, No. 1 (June and July, 1930), pp. 355–60 and 19–28.

10. G. F. Tagg, "The Earth Resistivity Method of Geophysical Prospecting" (some theoretical considerations), *Mining Mag.*, Vol. 43, No. 3 (September, 1930), pp. 150–58.

11. D. O. Ehrenburg and R. J. Watson, "Mathematical Theory of Electrical Flow in Stratified Media with Horizontal Homogeneous and Isotropic Layers," *Geophysical Prospecting* (*Amer. Inst. Min. Met. Eng.*) New York, 1932, pp. 423–42.

12. J. N. Hummel, "A Theoretical Study of Apparent Resistivity in Surface Potential Methods," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., New York, 1932, pp. 332–422.)

13. G. F. Tagg, "Earth Resistivity Surveying," *Eng. and Min. Jour.*, Vol. 131, No. 7 (April 13, 1931), pp. 325–26.

14. ———, "Practical Investigations of the Earth Resistivity Method of Geophysical Surveying," *Proc. Phys. Soc. London*, Vol. 43, No. 3 (May 1, 1931), pp. 238; 305–23.

15. I. Roman, "How to Compute Tables for Determining Electrical Resistivity of Underlying Beds and Their Application to Geophysical Problems," *U. S. Bur. Mines Tech. Paper 502* (1931), 44 pp.

16. G. F. Tagg, "Interpretation of Resistivity Measurements," *Amer. Inst. Min. Met. Eng. Tech. Publ. 477* (New York, February, 1932).

17. T. A. Manhart, "Contributions to the interpretation of resistivity curves," *Colorado School of Mines Master's Thesis*, April 1932.

18. L. J. Peters and John Bardeen, "Some aspects of electrical prospecting applied in locating oil structure," *Physics*, Vol. 3, No. 2 (March, 1932), pp. 103–22.

III. RESULTS OF RESISTIVITY METHODS

1. W. Peterson, "Das Aufsuchen von Erz mittels Elektrizität," *Glückauf*, Vol. 43, No. 29 (July 20, 1907), pp. 906–10.

2. O. H. Gish and W. J. Rooney, "Measurement of Resistivity of Large Masses of Undisturbed Earth," *Terr. Magn. and Atm. Elect.*, Vol. 30, No. 4 (December, 1925), pp. 161–88.

3. A. S. Eve and D. A. Keys, "Geophysical Prospecting: Some Electrical Methods," *U. S. Bur. Mines Tech. Paper 434* (1928), 41 pp.
4. F. W. Lee, "Measuring the Variation of Ground Resistivity with a Megger," *U. S. Bur. Mines Tech. Paper 440* (1928), 16 pp.
5. A. Belluigi, "Un metodo elettrico d'indagine del sottosuolo," *La Miniera Italiana*, Vol. 13 (September, 1929), pp. 329–31.
6. I. B. Crosby and E. G. Leonardon, "Electrical Prospecting Applied to Foundation Problems," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., 1929), pp. 199–211.
7. G. Carrette and S. F. Kelly, "Discovery of Salt Domes in Alsace by Electrical Exploration," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., 1929), pp. 211–21.
8. W. O. Hotchkiss, W. J. Rooney, and James Fisher, "Earth-Resistivity Measurements in the Lake Superior Copper Country," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., 1929), pp. 51–68.
9. A. S. Eve, D. A. Keys, and F. W. Lee, "Depth Attainable by Electrical Methods in Applied Geophysics," *U. S. Bur. Mines Tech. Paper 463* (1929).
10. E. G. Leonardon and S. F. Kelly, "Some Applications of Potential Methods to Structural Studies," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., 1929), pp. 180–99.
11. G. F. Tagg, "The Electrical Resistance Method of Geophysical Surveying," *Canada Min. Jour.*, Vol. 50, No. 49 (December 6, 1929), pp. 1156–59.
12. C. and M. Schlumberger, "The Method of the Ground Resistivity Map and its Practical Application," *Canadian Min. Met. Bull. 226* (February, 1931), pp. 271–94; *ibid.*, *Annales des Mines*, Vol. 18, No. 9 (1930), pp. 97–127.
13. A. Shaiderov, "On the Results of the Electrical Prospecting in the Region of Novo-Grozny," *Azer. Neft.*, *Khoz.* 10, No. 9 (1930), pp. 78–85.
14. ———, "Problems of Electrical Prospecting on the Grozneft Fields," *Azer. Neft. Khoz.* 10, No. 6 (1930), pp. 58–63.
15. D. Golubiatnikov, "Electrical Prospecting in the Region of Grozny," *Za. Neft., Prat.*, 11–12; 11–14 (1930).
16. C. and M. Schlumberger, "Depth of Investigation Attainable by Potential Methods of Electrical Exploration and Electrical Studies of the Earth's Crust at Great Depths," *Geophysical Prospecting*, Amer. Inst. Min. Met. Eng., New York, 1932, pp. 134–40.
17. T. Alty and S. Alty, "The Detection of Rock Salt by the Method of Electrical Surveying," *Canada Jour. Research*, Vol. 3, No. 6 (1930), pp. 521–25.
18. S. F. Kelly, "Electrical Methods for Subsoil Investigation," *Brooklyn Eng. Club Proc.*, Vol. 28, No. 3 (1930), pp. 22–41.
19. F. W. Lee and J. H. Swartz, "Resistivity Measurements of Oil-Bearing Beds," *U. S. Bur. Mines Tech. Paper 488* (1930).
20. C. and M. Schlumberger, "Memoire sur la méthode de la carte des résistivités et ses applications pratiques," *Congrès Inst. d. Mines, Met. et de la Géologie Appl.* (Liége, June, 1930).
21. Helmer Hedstrom, "Geo-Electrical Exploration Methods," *The Oil Weekly*, Vol. 58, No. 6 (July 25, 1930), pp. 34–36.
22. W. P. Jenny, "Electric and Electromagnetic Prospecting for Oil," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 9 (September, 1930), pp. 1199–1214.
23. N. Gella, "Geo-Electric Investigations of Non-conductors; Four New Examples," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 9 (September, 1930), pp. 1165–76.
24. K. Sundberg, "Electrical Prospecting for Oil Structure," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 14, No. 9 (September, 1930), pp. 1145–63.
25. E. E. Carpenter and E. G. Leonardon, "Geophysical Studies Predict Rock Conditions at Tunnel Site," *Engineering News Record* (September 4, 1930).
26. A. B. Edge and T. H. Laby, *Principles and Practice of Geophysical Prospecting:* II (2B) and VII (2): "Resistivity Methods" (Cambridge, 1931).
27. H. A. Buehler, *Missouri Bur. Geology and Mines Biennial Report* (Rolla, 1931), pp. 15–16, and Appendix III, pp. 146–61.
28. W. J. Rooney, "The Use of Resistivity Measurements in the Detection of Mineralized Areas," *Intern. Geod. and Geophys. Union Bull. 8* (Paris, 1931), Sec. Terr. Magn., pp. 352–53.

29. L. Gilchrist, J. B. Mawdsley, A. S. Eve, D. A. Keys, H. C. I. Watson, J. H. Swartz, "Studies of Geophysical Methods, 1928–1929," *Canada Geol. Survey Mem. 165*, No. 2266 (Ottawa, 1931), pp. 1–188.

30. E. V. Potter, "Results of Electrical Resistivity and Electrical Induction Measurements at Abana Mines, Quebec, Canada," *U. S. Bur. Mines Tech. Paper 501* (1931).

31. J. J. Jakosky, "Practical Aspects of Geophysical Surveys," *Arizona Min. Jour.* (January 15, 1931), pp. 18–29.

32. E. G. Leonardon, "Electrical Exploration Applied to Geological Problems in Civil Engineering," *Amer. Inst. Min. Met. Eng. Tech. Publ. 407* (February, 1931).

33. Joel H. Swartz, "Resistivity Measurements upon Artificial Beds," *U. S. Bur. Mines Circ. of Inf. 6445*, (February, 1931).

34. L. Gilchrist, "Measurements of Resistivity by the Central Electrode Method at the Abana Mine, NW. Quebec, Canada," *Amer. Inst. Min. Met. Eng. Tech. Publ. 386* (February, 1931).

35. Bela Low, S. F. Kelly, and W. B. Greagmile, "Applying the Megger Ground Tester in Electrical Exploration," *Geophysical Prospecting* (Amer. Inst. Min. Met. Eng., 1932), pp. 114–26.

36. M. K. Hubbert, "Results of Earth Resistivity Survey on Various Geologic Structures in Illinois," *Amer. Inst. Min. Met. Eng. Tech. Publ. 463* (February, 1932).

37. J. H. Swartz, "Oil Prospecting in Kentucky by Resistivity Methods." *U.S. Bur. Mines Tech. Paper 521* (1932).

38. C. A. Heiland, "A Demonstration of the Geologic Possibilities of the Resistivity and Magnetic Prospecting Methods," *Terrestr. Magn. & Atmosph. Elec.*, Vol. 37, No. 3 (September, 1932), pp. 343–50.

39. E. M. Poldini, "Les sondages électriques" *Bull. techn. Suisse Romande*, 1932.

40. C. and M. Schlumberger and E. G. Leonardon, "Location and Study of Pipe Line Corrosion by Surface Electrical Measurements," *Amer. Inst. Min. Met. Eng. Tech. Publ. 476* (February, 1932).

41. V. Melikian: "Electrical Survey of Limestones of the Bibi-Eibat Bay," *Azerbayjanskoye Neffyianye Khozyaistro, Baku*, Vol. 117–18, Nos. 9–10 (September-October, 1931), pp. 104–08.

### IV. POTENTIAL-DROP-RATIO METHODS

1. J. Koenigsberger, "Zur Ermittlung ausgedehnter Schichten verschiedener Leitfaehigkeit," *Zeit. Geophysik*, Vol. 6, No. 2 (1930), pp. 71–78.

2. ———, "Ueber geoelektrische Methoden mit direkter Stromzuleitung," *Gerland's Beitrage*, Suppl. 1 (1) (1930), pp. 23–109.

3. A. Broughton Edge and T. H. Laby, *The Principles and Practice of Geophysical Prospecting* (Cambridge Univ. Press, 1931). "Potential-Drop-Ratio Method," pp. 50–54, 119–26, 268–74.

4. ———, "Geo-Electrical Prospecting by A. C. Bridge Methods," *Chem. Eng. and Min. Rev.*, Vol. 23, No. 27 (April 6, 1931), pp. 249–51; *ibid.*, *Nature*, Vol. 127, Nos. 3192 and 3203 (January 3, 1931), pp. 37–39.

5. H. Lundberg and Th. Zuschlag, "A New Development in Electrical Prospecting," *Geophysical Prospecting*, Amer. Inst. Min. Met. Eng., New York, 1932, pp. 47–62.

6. H. Lundberg and F. Kihlstedt, "Differential Rate of Change Method; Elimination of Surface Resistivity Variation in Electrical Prospecting," *Amer. Inst. Min. Met. Eng. Adv. Paper* (February, 1932), 4 pp.

7. H. Hedstrom, "Electrical Prospecting for Auriferous Quartz Veins and Reefs," *Mining Mag.*, Vol. 46, No. 4 (April, 1932), pp. 102–19.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1337-1348

# USE OF GEOELECTRIC METHODS IN SEARCH FOR OIL[1]

O. H. GISH[2]
Washington, D. C.

## ABSTRACT

Factors which have adversely influenced opinions and general impressions regarding the value of geolectric methods as aids in the search for oil are thought by the author to be in considerable part of subjective rather than objective origin. However, geoelectric methods entered the field relatively late and with inadequate theoretical equipment for the best interpretation of results. Furthermore, sources of error which doubtless vitiated results have been in some cases overlooked because these did not come into serious account in the previous experience of exploration for ores. The principal sources of error for the resistivity method are pointed out. Although electromagnetic and resistivity methods have shown distinct promise in this field, it is, in the author's opinion, not possible with the data now available to make a reliable comparison, in terms of potential results per dollar, between these and gravimetric or seismic methods.

Published pronouncements on the success of geophysical methods as aids to the geologist in the search for oil have been numerous and various. It is not intended here to add to the number and it would be quite impossible to add to the variety. A careful quantitative appraisal of any one method would require the consideration of many factors and would accordingly call for a statistical analysis of a great mass of data. If all the data now resting in the files of various organizations were pooled, they would probably be adequate for such a study, at least in the case of those methods which have been used most extensively. Unless and until such a study can be made, a considerable diversity of opinion, as to the degree of success of a given method under the various conditions thus far encountered, may be expected to continue. Such studies of individual methods would constitute an important preparation for the much more difficult task of evaluating the relative merits and determining the particular province of each of the different methods. And then there would remain for consideration the advantage which accrues from the joint use of two or more methods.

[1] Manuscript received, July 21, 1932.

[2] Department of Terrestrial Magnetism, Carnegie Institution of Washington. Introduced by F. H. Lahee.

Statistical studies of these questions may seem so laborious as to be uneconomical. However, the variables which are not under man's control are here so numerous that the statistical along with all other means of attack must be used. It is feared that the importance of considering geophysical problems and data from a statistical viewpoint is not fully appreciated.

The physicist coming from his problems in the laboratory where accessory factors are largely under his control, on his early encounters with geophysical problems is likely to be either over-optimistic or pessimistic, according to temperament. Although his technique and thorough knowledge of the underlying principles of method and apparatus are needed, yet he is likely to be handicapped at the outset by a lack of that "statistical sense" which is so necessary in the successful geophysicist and which is generally acquired only with time and experience. Unfortunately, some persons, otherwise well qualified, seem unable to acquire this sense or judgment and as a result continue for years to harass editors and to clutter up the literature of geophysical science with pet theories and general conclusions based on inadequate data or even trivial manifestations.

One in whom this statistical sense is lacking is likely either to extol or to condemn a method after too brief a trial. In either case he may be unaware not only of the many phenomena of the earth which act as disturbing influences, but also of the fact that many suitably distributed data, or samples, are required under such circumstances before a reliable interpretation can be made or a decision either for or against a method is justifiable. Both experience and temperament go to determine the extent to which a judicious balance may be maintained between optimism and pessimism when evaluating methods or interpreting results.

The element of uncertainty in the final interpretation of a geophysical survey must be not only recognized but also admitted by the geologist and the geophysicist who share jointly the responsibility for the interpretation. The enthusiast can do real harm by leading the patron to expect too much of geophysical methods and thus add to the damage already wrought by self-styled "geophysicists" of either the unscrupulous or the incompetent variety. This probably applies with especial force in the case of geoelectric methods. The quack and the shyster seem to have a strong predilection for electrical vestments.

Another unfortunate circumstance is that electrical trappings are,

in the minds of many laymen, endowed with mystical power. No doubt everyone who has worked with geoelectric methods has been amused by the curious spectator who loses all interest when he finds that the apparatus in use is not provided with a pointer and scale to indicate the number of barrels of oil which may be obtained from a well sunk at a particular spot. But it is not only the curious spectator who entertains this attitude. In recent years some hard-headed business men in an eastern oil field patronized a self-styled geophysicist who with a voltmeter and a few vacuum tubes connected in a meaningless circuit professed to perform this miraculous feat. The vacuum tube is the superb present-day garnishment for the doodlebug and doubtless whets the appetite of those who have a taste for this morsel.

The bonafide geophysicist will, of course, not make such pretentious claims. He will recognize in his task a parallel to that of the weather-forecaster and will not shrink from using that qualifying word, "probable." He will speak only of indications, good, bad, or indifferent. These should be among the passwords, without which an entrance into the confidence of prospective patrons can not be won.

Although some geoelectric methods may under favorable conditions detect oil directly because of its high insulating property, geoelectric as well as other methods are efficacious in the location of oil only to the extent that they disclose subsurface structural features which in turn may indicate oil-bearing structure. That geoelectric methods are capable of disclosing hidden structure had been definitely shown before these methods were tried in the oil field, and since then a number of cases in which geoelectric surveys disclosed oil-bearing structure have been reported. Some of these are mere statements and have to be accepted on faith, but in several reports data are published which seem definitely to support the claims.

It is, of course, obvious that structure will be revealed by any geophysical method only when that property of the structure upon which the method depends presents a certain degree of contrast to the surroundings. Thus two different methods, as, for example, the gravimetric and the electric, may reveal entirely distinct structures, or one method may give indications of structure while the other does not. It must not be assumed, however, that the method which gives no indication is not of positive value, for if the information which it supplies is considered along with that obtained by the other method,

then more definite conclusions as to the nature of the structure are likely to be justified.

The electrical conductivity, or the resistivity, of earth materials is the electrical property upon which those geoelectric methods which have shown some promise in the oil field depend. Methods employing radio waves would, of course, respond to differences in the dielectric constant and some entertain hopes for such methods. Perhaps, when the technique for sending directed beams of radio waves is sufficiently developed some success will be enjoyed by these methods.

The resistivity of earth materials varies between great extremes. Thus of the materials which come into account in the oil field, salt water, at one extreme, may have a resistivity as low as 10 ohm-centimeters, whereas the value for the igneous bed rocks, the other extreme, may run high in the millions of ohm-centimeters. Oil itself has very high resistivity, but to utilize this property for direct detection requires a relation between the extent of the pool and the depth from surface which probably occurs only rarely. Although some claims of direct detection have been made, the evidence presented is not conclusive.

The diversity in the resistivities of earth materials is far greater than that of any other property upon which geophysical methods depend. This is, however, not the advantage that it may at first thought seem. One reason for this is that the condition for detecting structure does not continue to improve indefinitely as the contrast in resistivity increases, but a limit is soon approached where "enough is as good as a feast." Most of the benefit is obtained when the resistivities differ by a factor of 100. Another reason is that this great diversity increases the chance that inhomogeneities within a structure and even small local differences in constitution may act as disturbing factors. Of course, if the data are obtained in such a way as to constitute an adequate sampling, then by suitable treatment in which these disturbing effects are regarded as accidental errors of observation they can be largely smoothed out. Such disturbing effects are doubtless met with to some extent in all geophysical measurements. Their magnitude is a determining factor both as regards the number and the distribution of observations required in a survey in order that reliable indications of the more general features may be obtained. This is also a factor which plays a part in determining the optimum sensitivity of the measuring instruments. Thus, if the accidental

errors of observation are about one-tenth the magnitude of the disturbing effects, the measurements are doubtless of adequate precision. Greater precision may make the work unduly tedious and lead to confusion. This does not apply to systematic errors of measurement. Advantage may accrue if these are of an order of lower magnitude than that of the accidental errors.

The various electric methods which have been in use for one or another phase of geophysical exploration may be classed as follows: radio methods, electromagnetic methods, equipotential methods, resistivity methods, and miscellaneous electric methods. It appears that of these the electromagnetic and the resistivity methods have enjoyed a measure of success in the exploration for oil. When this is taken along with the fact that, in comparison with gravimetric and seismic methods, these electric methods are late comers in this field, their present prospects seem good.

The introduction of electrical methods into the more difficult phases of exploratory work has doubtless been hindered by the tardy development of a quantitative theoretical basis for the interpretation of the electrical survey data. In the case of seismic and gravimetric methods such a basis had been fairly well developed through their years of use in the basic studies of geophysics. The theoretical problems presented by the electric methods are more complicated, but these have been attacked in recent years by several investigators and the results obtained are of considerable practical value. This is especially true of those investigations which apply to resistivity methods. The detailed solutions here are restricted to the simpler ideal cases, but these provide norms with which survey results may be compared. It is to be expected that calculations will be extended to include other typical cases and that in the near future methods to facilitate such calculations will also be developed.

From the theoretical considerations it appears that geophysical measurements alone will admit of a unique quantitative interpretation only in special cases. Of the several interpretations which would be consistent with the measurements, some may be eliminated as being incompatible with facts known to the geologist. The number of possible interpretations is likely to be further reduced if surveys by more than one method are made. Thus, by the consideration of other information along with the survey data, it seems possible to decide upon one as the most probable interpretation. When there is added to

this the data from a single test hole, the structure of the region covered by the survey should be determinable in many cases.

Interpretation of some aspects of geoelectric surveys has often been made with the aid of empirical rules, for which no satisfactory theoretical support has yet been found. A few remarks on one of these, for which the writer bears some responsibility, may be of interest. In that form of development of the resistivity method where four electrodes are set in line at equal intervals, it was at the outset tentatively considered that the distance between adjacent electrodes was a rough measure of the depth of earth involved in the measurement. This rule seemed to do better service than was expected. Such checks as it was possible to make strengthened confidence in it, and even to the present time some geophysicists with extensive experience in geoelectric work continue to use it even though they are aware that the theoretical considerations of recent years give no general support to such a rule. The observational data now available to most workers are probably inadequate to determine whether there is a conflict here between fact and theory. The theory seems sound, except for the assumption that earth materials are isotropic as regards the property of resistivity. There seems to be considerable evidence that this assumption is not justified, but that the resistance to electric flow in a horizontal direction is different from that in a vertical direction. A more general theory, embracing eolotropic materials, is, because of its difficulty, not likely to be developed unless overwhelming evidence is adduced to show that the simpler theory is inadequate. Hence at present it would seem best to use the theory now developed as a guide in the interpretation of resistivity surveys.

One who is confronted with the task of selecting an electric method for use in the search for oil will find his chief difficulty in making a choice between electromagnetic and resistivity methods. If he has had experience with one of these, he will probably do well to select that method, for in "the present state of the art" success depends to a considerable extent upon familiarity with the method and apparatus, and this is not gained in a day. The remarks which follow may help to elucidate this and, at the same time, call attention to some systematic errors which have not always been avoided in resistivity measurements.

In 1922 the writer gave consideration to various possibilities of obtaining a measure of the resistivity of large masses of undisturbed earth. Such data were desired in connection with investigations of the

natural electric currents in the earth which were then being initiated in the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. The method of measurement which was finally decided upon should be regarded as a direct-current method.[1] It was thought that with this method it should be easier to carry out surveys, especially when great depths of earth are to be included in the measurements, and that the interpretation should be simpler than for a number of other possibilities which were examined. This method is an improvement and extension of that developed by McCullom[2] and used by him in electrolysis surveys and which was in turn based on an alternating-current method suggested by Wenner.[3] The first preliminary survey, made in the early autumn of 1924 with the apparatus designed for large-scale measurements, showed that the method could be used for determining and locating structure under certain circumstances. Following the publication of a report on this work, the method was adopted in some form by several organizations which had previously made extensive use of equipotential methods. In response to requests in recent years, working drawings and other information required for the duplication of the apparatus have been supplied by the Department of Terrestrial Magnetism to a number of responsible individuals and research organizations. It appears from reports, published by some of these, that a few of the more essential features of the apparatus have at times been overlooked or misunderstood. The fact that this occurred, even where the work was in charge of capable physicists, indicates the need of the additional emphasis which a restatement of these features may give.

There are situations where the detection of the desired structure is so simple that relatively crude apparatus will suffice. However, when the exploration is to extend to greater depths, in the hundreds and into the thousands of feet, and under conditions which are made difficult by the relationship between the conducting and non-conducting strata, success is dependent upon careful attention to the following matters: (1) the polarization, contact potentials, and earth potentials of various origin of the pick-up electrodes must be largely eliminated; (2) the effects of induction between the two circuits must be made negligibly small; and (3) the insulation between the relatively high-potential energizing circuit and the low-potential pick-up

[1] *Terr. Mag.*, 30 (1925), pp. 161–88; *Bull. Nat. Res. Council*, 11, Pt. 2 (1926), pp. 86–91; *U. S. Patent No. 1, 813, 845* (1931).

[2] "Measurement of Earth Currents," *Elec. Ry. Jour.* (November 5, 1921).

[3] *Bull. Bur. Standards*, 12 (1916), pp. 469–78.

circuit must be maintained in a much better condition than is required in the more common electrical measurements or else some provision must be made in the design to obviate the effects of leakage currents.

In the apparatus developed at the Department of Terrestrial Magnetism by the writer, the contact potentials, etc., are eliminated by employing a double commutator which reverses the energizing current about twenty times per second and at the same time rectifies the pick-up current so that a direct-current potentiometer may be used in this part of the measurement. If this is to be satisfactorily accomplished, the commutator must be carefully made and properly adjusted. When the contact potentials, for example, are very large, 0.5 volt and upwards, the forced vibration of the pointer of the potentiometer-galvanometer becomes so great that settings are difficult. This difficulty is eliminated if a condenser of about 20 microfarads capacitance is thrown in series with one of the pick-up lines. The condenser should not be required when the contact potentials are much less than 0.5 volt unless the galvanometer has characteristics which make it unsuitable for this work or the adjustment or construction of the commutator is defective. If the latter be the cause, serious systematic errors may enter the measurements.

The effects of induction between the two circuits can be very serious, especially when measurements are being made with long lines. Some workers have attempted to correct for the effects by obtaining measurements at two different and known rates of commutation, but in the opinion of the writer this is not satisfactory either in theory or in practice. These induction effects may, however, be avoided if the potential between the pick-up points is measured only during that part of the cycle when the energizing current is constant. That this can be accomplished automatically if the commutator is designed and adjusted with this end in view has been demonstrated by many comparisons made by W. J. Rooney.[1] It is, of course, obvious that if the commutator in the present form should be used with lines many times the length of any employed heretofore in surveys, the time constant of the circuit may become so great that adjustment would no longer be possible. It should also be mentioned that an improperly adjusted commutator can falsify the potential measurements by effectively shunting the potentiometer during a part of the cycle.

Errors from defective insulation may at times be very great. During early experience in this work, errors of several hundred per cent

[1] *Terr. Mag.*, 35 (1930), pp. 61–72.

were found on a few occasions. It is when these give rise to negative values in the calculated resistance that they are especially conspicuous. With some types of apparatus which have been used in resistivity surveys, such absurd results are not forced upon the attention of the observer, but the error is not less serious for his being unaware of it.

The errors which may arise from defective insulation on the field cables are nearly always additive. It is only for some unusual positions of the cables that they cause the measured values to be too small. However, in all our experience, errors from this source have been inappreciable except on a few occasions when old cables were used in rainy weather.

It is in the instruments that troublesome insulation defects may develop. The errors which result from these are in part dependent upon the relationships between the circuits in the instruments and upon the contact resistance of the electrodes. Since both these factors may be varied to some extent, this provides a means of detecting such errors. Four different circuit relationships are readily obtained by changing the connections of the field cables with the instruments. The values of resistivity obtained from measurements with these different combinations may all differ if leakage effects are present. Their mean is in general not free from leakage error as has been assumed by some. These errors are completely eliminated from this mean only when the contact resistances of the pick-up electrodes or those of the energizing electrodes are equal, and this holds only if the condition of the insulation remains constant during the series of measurements.

The uncertainty and inconvenience which attend attempts to eliminate these errors by such means can, however, be avoided by making suitable provisions in the apparatus. The device which has been adopted for this purpose is similar in conception to the "guard ring" which is often used, especially in instruments employed for measuring very small quantities of electricity. This consists essentially of an independent system of conductors so arranged as to intercept all possible paths by which current may leak from the energizing circuit to the pick-up circuit. If this guard system is connected to earth at a relatively neutral point, its potential is maintained at a value which differs so little from that of the pick-up circuit that this serves to reduce such errors to several orders' lower magnitude than those which would result if this device were not employed. In thousands of tests made by W. J. Rooney under a wide variety of con-

ditions, no evidence of errors from this source has ever been found when the "guard" was in use.

The foregoing rather technical remarks apply when a commutator is used in the resistivity measurements. Resistivity surveys have, however, been carried out without employing a commutator but by using, instead, simple hand-operated switches. The errors which may enter into measurements made by such a method include those which have been discussed for the case where a commutator is used. Of these, that type which arises from the various extraneous potentials which act upon the pick-up electrodes is likely to be much more serious with this method than with the commutator method. This is partly because, even with the best technique, the time required for a single setting of the potentiometer and the interval between readings for reversed current are both so long in comparison with the corresponding cycle in the commutator method that the error in the result is likely to be considerably greater on this account alone. On the other hand, a single reading obtained by the use of a commutator is effectively a mean taken over a considerable number of cycles and on this account is of enhanced accuracy in cases where errors of a random nature may be appreciable. In the simple switching method, errors due to defective insulation may be controlled by the design and arrangement of the switches, whereas induction effects will depend upon the technique of measurement. As far as the last two sources are concerned, the results obtained with the simple method should be better than those obtained with an unsuitable commutator. The writer is, however, of the opinion that if the possibilities of the direct-current resistivity method are to be fully realized, suitable mechanical means of rapid commutation are required.

The search for oil often requires exploration to greater depths than was required in the earlier applications of geoelectric methods, namely, in the search for ores. Views as to the capability of geoelectric methods for such deep exploration vary, whether these be based upon theory or practice. Obviously the details of structure will become less distinct the greater the depth from the surface. Thus, a feature of the hidden structure can be detected at the surface only when it is of sufficient extent. The necessary relation between depth and extent is dependent upon the accuracy of the measurements and upon the magnitude of the uneliminated influences of the disturbing features of the earth. The accuracy of the measurements can be controlled by suitable design and operation of the measuring apparatus. The errors

arising from disturbing features of the earth, such as topography and inhomogeneities within structure, are to a considerable extent dependent upon the number and the distribution of measurements and upon the method by which these data are treated. In order that corrections may be made for the more general features of topography, a further development of theory is required.

Although there is some evidence that features of structure located between 2,000 and 4,000 feet below the surface have been disclosed by resistivity surveys, this is by no means definitely established. General theory, as the writer understands it, does not exclude such a possibility. In fact, the likelihood of exploring to far greater depths seems so good to some of us that plans are being developed for a large-scale coöperative undertaking in which it is hoped to obtain by resistivity measurements information about the structure of the earth's crust down to a depth of about 50 miles. The results to be obtained from such a venture are, of course, not expected to be of practical value, except perhaps indirectly, but they should have important bearing on problems in several branches of the basic science.

The principal points which it has been attempted to bring out in this article may be briefly stated as follows. Although evidence is at hand showing that some geoelectric methods are aids in the search for oil, yet it can not be determined at this time whether the results per dollar from these methods compare favorably with those obtained from gravimetric or seismic methods.

An attitude of disfavor toward geoelectric methods has perhaps in considerable part sprung from subjective rather than objective sources. The widespread belief in the near-omnipotence of electricity has brought forth many impotent geoelectrical schemes and has provided easy prey for these as well as for the outright faker. Of course, an unfavorable reaction followed. Furthermore, a bonafide geoelectric method can not qualify as the idol of these "believers."

Geoelectric methods also entered this field with the handicap of inadequate theoretical equipment and with practical experience in a class of problems not adapted to bring out some details of apparatus and method important in the more difficult work to be encountered here. These conditions doubtless added considerably to the cost and lessened the value of the results obtained from some of the geoelectric surveys. And withal there is the seniority of gravimetric and seismic methods to be considered.

In principle it seems entirely feasible in many cases to determine

from the data of resistivity surveys, taken along with other information which can be supplied by the geologist and the petroleum engineer, the approximate depth and the features of the more general structure associated with petroleum resources.

Reports of actual tests seem to bear this out, perhaps rather too well in some cases. This applies especially to some recent tests which came to attention[1] as this conclusion was being written. These consisted of the correlation of hundreds of drill-hole records with results of resistivity surveys made by five different parties in as many different oil fields in Russia. According to the abstracts, one of the articles contains the conclusion that "more tests are required to draw definite conclusions on the degree of usefulness" of this electric method. This leaves one uninformed as to whether or not any indication that the method may prove useful was found. However, there is no ambiguity in the four other conclusions, which run as follows: "This method is of great importance in geological interpretation of the subsoil and should be used on a large scale"; "whether the mechanical coring can entirely be substituted by this method or not can not be definitely decided at present." One in which 180 drill-holes were investigated concludes that this "must be recognized as one of the most useful and necessary methods of determining the correlations in the stratigraphical conditions of oil deposits." In what appears to be the most extensive of the five investigations 220 drill holes were covered. In the report of this it is concluded that "the great advantage of electrical coring is established." The full reports may restrict some of these conclusions more than is indicated in the abstracts.

It is perhaps utopian to wish that these investigations had also included surveys by the other outstanding geophysical methods. An investigation of such scope should have considerably lessened the element of guesswork which is involved in making a choice from the several available methods. The writer is not impelled to venture such a guess here; he is, however, convinced that some geoelectric methods will in due time be accepted as useful aids in the search for oil.

[1] *Geophys. Abstr., No. 37* (1932), pp. 450–53.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 16, NO. 12 (DECEMBER, 1932), PP. 1349-1356, 3 FIGS.

# CORRELATION BETWEEN RADON AND HEAVY MINERAL CONTENT OF SOILS[1]

R. W. CLARK[2] and HOLBROOK G. BOTSET[3]
Pittsburgh, Pennsylvania

## ABSTRACT

The presence of radon in the soil cannot be used as a criterion for locating oil fields, since the source of the radon lies in the radioactive minerals of the soil and not in the petroleum at greater depths. Formation contacts could be located by a radon survey even though obscured by top soil and vegetation, because there is quite likely to be a difference in heavy mineral character and content of two different formations. Likewise faults may be indicated if they bring two quite different formations into juxtaposition, but there is always danger of misinterpreting variations in the radon content of a soil which may be due simply to local variations in the amount of radioactive minerals in one and the same formation.

## INTRODUCTION

In recent years radioactive methods of geophysical prospecting have attracted some attention. Most prominent among these methods has been that of measuring the radon content of soils[4] and attempting to deduce from these results the nature of the geological substrata. Radon is one of the constituents of the soil gas and is the immediate decay product of the metallic element radium. The radon itself is radioactive and its radioactivity per unit of weight is several times that of radium, thus enabling extremely small quantities of the gas to be detected. It is claimed that a fault will be evidenced by a higher radon concentration in the overlying soil,[5] and that the radon content of the soil above an oil bearing formation is higher than elsewhere.[6] Since there were no data available as to the success or failure of these radioactive methods in this country, an extensive study was made of the radon content of soils in regions whose geology and lithology were

[1] Manuscript received, June 23, 1932.

[2] Geologist, Gulf Companies.

[3] Physicist, Gulf Research Laboratory.

[4] "Radon Content of Soil Gas," H. G. Botset and Paul Weaver, *Physics*, Vol. 2 (1932), pp. 376–85.

[5] F. Müller, "Radioaktivitälsmessungen als geophysikalische Aufschlussmethode," *Zeits. für Geophysik*, Vol. 3, No. 7 (1927), pp. 330–36.

[6] L. N. Bogoyavlensky, "Radiometric Exploration of Oil Deposits," *Bull. Inst. Practical Geophysics* (Leningrad), No. 3 (1927), pp. 113–24.

quite well known. The authors acknowledge their indebtedness to A. E. Ruark, of the University of Pittsburgh, and Paul Weaver, Houston, Texas, for valuable suggestions in the conduct of this work.

## APPARATUS AND FIELD METHODS

The measurements were made in soils which were developed over sedimentary formations consisting predominantly of sandy clays with

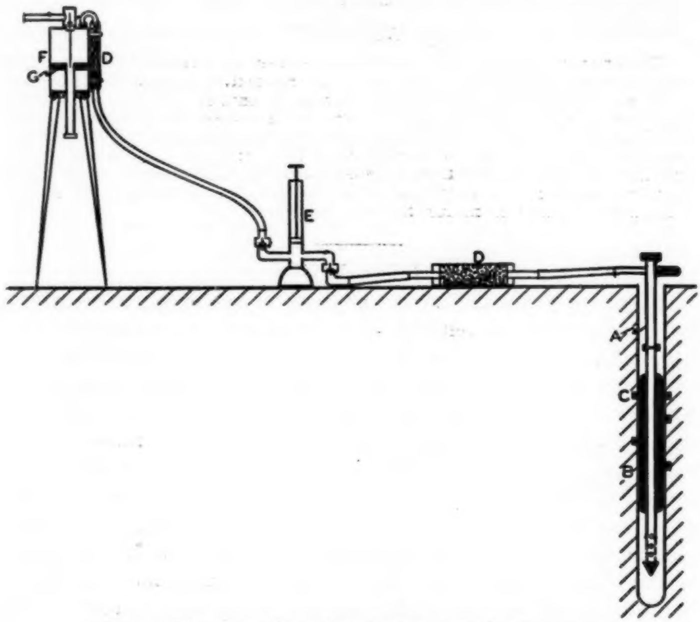



FIG. 1.—Diagrammatic section of radon measuring apparatus.

some slightly consolidated sands, all of Tertiary age. Most of the measurements were made in wooded areas, but some were in cultivated fields, and some in natural prairies.

The technique of making the measurements is a modification of the method developed by Ambronn.[1] The equipment used is shown diagrammatically in Figure 1. The hole into which the sampling tube is placed is made by first driving a steel rod into the ground about a foot and then continuing the hole with an earth auger. This is to

[1] R. Ambronn, *Elements of Geophysics*, English translation by Cobb (1928), p. 119.

avoid compacting the soil around the hole and thus reducing its porosity, which would tend, in clayey soils, to make it more difficult to obtain a sample of soil gas. The sampling tube (*A*) consists of a 1¼-inch iron pipe, broken and coupled near the top to permit the insertion of nipples so that the tube can be extended when samples of soil gas from greater depths are desired. A wall packer (*B*) is welded on the outside of this tube about a foot from the bottom. The packer consists of a piece of tubing of the same diameter as the hole, around which an iron rod (*C*) of ¼-inch square cross section was wrapped spirally and welded in place. This rod cuts into the walls of the hole and forms a tight seal against leakage from the atmosphere. The gas sample is pumped through drying tubes (*D*) by the piston pump (*E*) into the ionization chamber (*F*) of the electroscope. The ionization chamber is a cylinder whose bottom is a movable piston (*G*). To empty the ionization chamber of gas the outlet cock on the top is opened and the piston pushed up. The outlet cock is then closed and the inlet opened. The gas sample being pumped in thus exerts an outward pressure on the system and any leakage occurring is outward. This prevents the dilution of the gas sample with atmospheric air. The minute traces of radon in the soil gas, by virtue of radioactive decay, produce an ionization of the gas in the ionization chamber and discharge the electrometer fiber which has been previously charged to a potential of about 200 volts. The rate of discharge is proportional to the amount of radon present in the gas. The sensitivity of the instrument is such that one part of radon can be detected in about $10^{12}$ parts of soil gas.

Several profiles were run across a known fault in the Balcones fault region. The measurements made in these profiles are shown in Figure 2. It is difficult to express the results in terms of quantity of radon per cubic centimeter of soil or per gram of soil mineral, because of the great variation in the porosity of the soil and because of another factor which may be even more variable, the so-called emanating power of the soil grains. Since the radon gas is the product of the decay of radium atoms, the radon must be formed on the surface of the soil grains or within the grains themselves. As the radon is a gas formed from a solid, only that part formed at the surface of the grains is able to get into the soil gas. The emanating power is the ratio of the amount of radon which gets into the soil gas to the total formed in the soil. This obviously depends, then, not only upon the size of the soil grains, but upon their shape (ratio of volume to surface) and upon

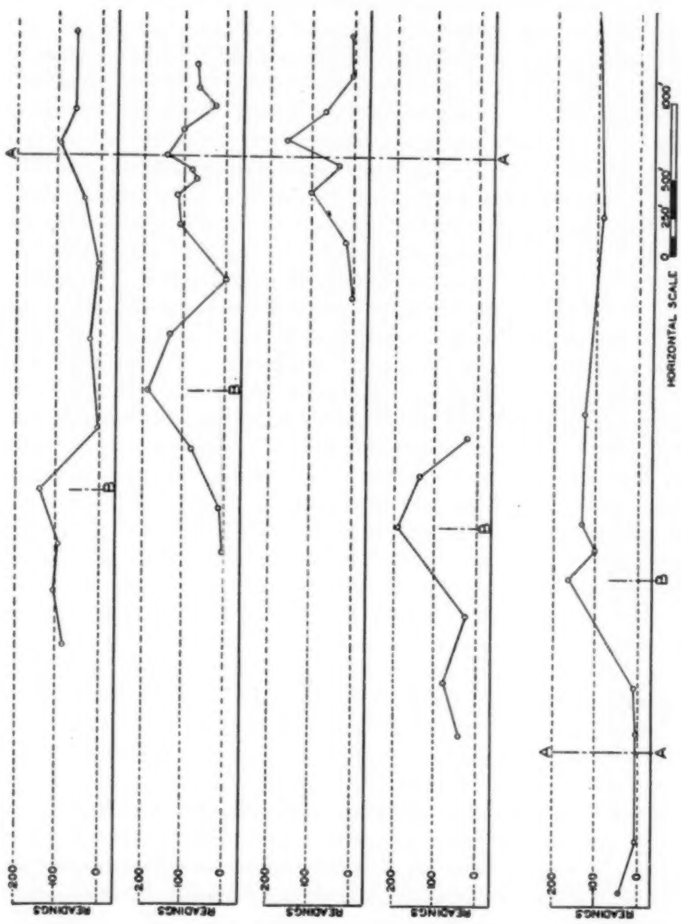



FIG. 2.—Radon profiles across a fault, *A*.

whether the parent radium has been deposited near the surface of the grain (secondary deposition), or whether it is distributed more or less uniformly throughout the grain. Naturally radium formed from uranium salts deposited chemically on the surface of the grains will have a large emanating power, while that formed in minerals in which the uranium was originally incorporated will have a lower emanating power. According to Satterly[1] the emanating power of a soil may vary from one-sixth to one-twentieth. Consequently, the ordinates of the curves presented here are expressed simply as electroscope readings, no account being taken of the variations in emanating power of different soils. These ordinates are divisions per second of movement of the electrometer fiber multiplied by 1,000. A calibration measurement on the electroscope made by using a known quantity of radon showed that an electroscope reading of 100, that is an actual rate of movement of the electrometer fiber of 0.1 division per second, was produced by $1{,}539 \times 10^{-12}$ curies of radon in the ionization chamber. The curie is the amount of radon in equilibrium with one gram of radium. If we assume a soil porosity of 33 per cent, $1{,}539 \times 10^{-12}$ curies in the electroscope would correspond to about $0.57 \times 10^{-12}$ curies of radon per cubic centimeter of soil.

As will be seen from Figure 2, an attempt to locate the fault by radon measurements would be very misleading, since the radon values obtained at the points marked *B*, where there is no fault, are just as high as, or higher than, those obtained at *A*, where the fault is actually located.

In order further to study the radon content of soils, surveys were made over the South Liberty salt dome. This dome has at present very little elevation above the surrounding terrain. The center of the dome is crossed by a small river. The eastern edge of the dome is a producing oil field. It is claimed by Bogoyavlensky[2] that an oil field will be indicated by a change in the radioactivity of the soil. To test this statement a profile was run across the producing section of the dome, starting from the outside edge of production and extending toward the center of the dome some distance beyond the producing area. The result of this survey is shown in Figure 3. The holes from which samples were taken for these measurements were 5 feet deep. The higher radon concentration in the producing area is obvious. After these results were obtained the profile was extended eastward

[1] J. Satterly, *Proc. Cambridge Society*, Vol. 16 (1911–12), pp. 336, 356, 514.

[2] *Op. cit.*

off the dome for at least ½ mile, and the radon content was still practically as high as was found in the producing area. This seemed to indicate that the presence of oil had little to do with the radioactivity of the soil.

Knowing the association of radioactivity with heavy minerals,[1] it was decided to make another profile parallel to and near the first and to take samples of the soil from the bottom of each hole. These samples were taken to the laboratory for quantitative determination of their heavy mineral content.

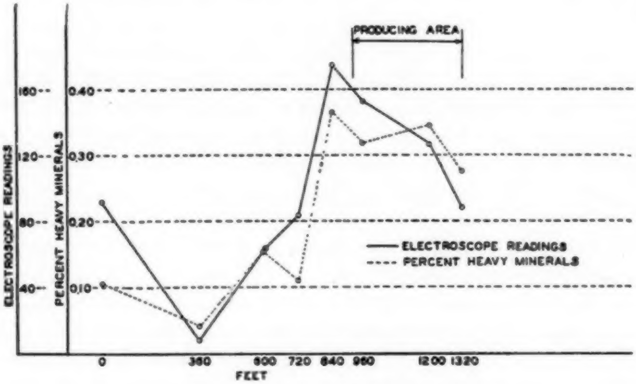



FIG. 3.—Radon profile across South Liberty salt dome.

## HEAVY MINERAL SEPARATION

About 30 grams of each of these samples were ground to pass a 130-mesh sieve. The heavy minerals were first separated by using bromoform in a separatory funnel. This bromoform had a density, as determined by the pyknometer, of 2.5. It was found, however, that the heavy mineral fraction obtained by this separation contained quartz and calcite. Consequently, this heavy mineral fraction was again separated, Thoulet's solution (density 3.15) being used. This gave a very complete separation and was adopted as standard procedure.

[1] E. H. Büchner, *Jahrb. f. Radioakt.*, Vol. 10 (1913), p. 516.
W. Waters, *Phil. Mag.*, Vol. 19 (1910), p. 903.
R. H. Strutt, *Proc. Roy. Soc.*, Vol. 84 (1910), p. 377.
A. Gockel, *Die Radioaktivität von Boden und Quellen* (Braunschweig, 1914).
St. Meyer and Schweidler, *Radioaktivität* (Leipsic, 1927).

The following table taken from Gockel will indicate some of the heavy minerals associated with radioactivity.

TABLE I

| *Mineral* | *Location* | *Radium per Gram of Mineral×10¹² Grams* |
|---|---|---|
| Zircon | Kimberley | 19.1 |
| Eudalite | Greenland | 12.6 |
| Orthite | Sweden | 236.0 |
| Gadolinite | Hitterö | 156.0 |
| Keilhanite | Alve, Norway | 452.0 |
| Niobite | Connecticut | 97.0 |
| Apatite | Canada | 14.6 |
| Cerite | Sweden | 30.0 |

The average radium content of sedimentary rocks is about $1.4\times 10^{-12}$ grams[1] per gram of rock. Thus it is seen how considerably the radioactivity is concentrated in the heavy mineral constituents.

Petrographic examination of the heavy mineral residues from the South Liberty dome revealed the presence of zircon, rutile, brookite, tourmaline, magnetite, ilmenite, apatite, biotite, augite, and cyanite. Zircon, tourmaline, and magnetite are the most abundant in all the samples examined. If the radioactivity of the soil could be ascribed to the mineral composition of the soil itself rather than to any deep-seated source, zircon is the one mineral of all those observed that is the most likely to be radioactive. F. L. Hess[2] describes a considerable number of unusual rare-earth minerals occurring in some of the igneous rocks of the central mineral region of Texas. Since this area was probably the source of much of the material of the late Gulf Coast Tertiary, these minerals were undoubtedly present to some extent in the soils but not recognized in the heavy mineral residues examined. In these minerals are such rare-earth elements as thorium and uranium. Thorium is the parent of one series of radioactive substances and uranium is the parent of the radium series and probably also of the actinium series. Since these elements (uranium and thorium) are isomorphous with zirconium, it is only logical to look for a possible relationship between the radon content of the soil and the amount of zircon and other rare-earth minerals in the soil. Experimentally, only the total heavy mineral content of the soil was determined, since zircon was always present in large percentages in the residues and not all the possible sources of radioactivity could be differentiated and segregated.

[1] G. Kirsch, *Geologie und Radioaktivität* (Berlin, 1928), p. 46.

[2] "Minerals of the Rare-Earth Metals at Baringer Hill, Llano County, Texas." *U. S. Geol. Survey Bull. 340* (1907), pp. 286–94.

Figure 3 shows almost a parallelism between the radon content of the soil and its heavy mineral content. This is one of many profiles across the South Liberty dome, all of which are generally similar. Such an abundance of corroborative evidence leads one to conclude that the radon content of soils is directly related to and due to the presence of radioactive minerals in the soils.

## CONCLUSIONS

The presence of radon in the soil cannot be used as a criterion for locating oil fields, since the source of the radon lies in the radioactive minerals of the soil and not in the petroleum at greater depths. Formation contacts could be located by a radon survey even though obscured by top soil and vegetation, because there is very likely to be a difference in heavy mineral character and content of two different formations. Likewise faults may be indicated if they bring two different formations into juxtaposition, but there is always danger of misinterpreting variations in the radon content of a soil which may be due simply to local variations in the amount of radio-active minerals in one and the same formation.

# THE ASSOCIATION ROUND TABLE

## MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

### FOR ACTIVE MEMBERSHIP

William Ernest Victor Abraham, Nyaunghla, Upper Burma
Sidney Powers, L. Murray Neumann, Edmond O. Markham

John C. May, Santa Barbara, Calif.
L. C. Decius, J. A. Taff, J. H. Jenkins

Milward Miller, Roswell, N. Mex.
T. F. Petty, J. B. Headley, L. T. Barrow

### FOR TRANSFER TO ACTIVE MEMBERSHIP

Robert Brown, Shawnee, Okla.
Sidney Powers, Jess Vernon, Dollie Radler

Charles Webster Flagler, Maracaibo, Venezuela, S. A.
Hollis D. Hedberg, P. E. Nolan, C. A. Baird

# INDEX TO VOLUME 16

Cl